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Biological Services Program

FWS/OBS-77/51
March 1980

Biological Impacts of Minor Shoreline Structures on the Coastal Environment: State of the Art Review

VOLUME I

Fish and Wildlife Service

U.S. Department of the Interior

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- To strengthen the Fish and Wildlife Service in its role as a primary source of information on national fish and wildlife resources, particularly in respect to environmental impact assessment.
- To gather, analyze, and present information that will aid decisionmakers in the identification and resolution of problems associated with major changes in land and water use.
- To provide better ecological information and evaluation for Department of the Interior development programs, such as those relating to energy development.

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FWS/OBS-77/51
March 1980

BIOLOGICAL IMPACTS OF MINOR SHORELINE STRUCTURES ON THE COASTAL ENVIRONMENT: STATE OF THE ART REVIEW

VOLUME I

by

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PREFACE

This report was written for fish and wildlife biologists who review permits for the construction of minor shoreline structures in the coastal environment, and was submitted in fullfillment of Contract 14-16-0008-2153.

Any suggestions or questions regarding this review should be directed to:

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SUMMARY

Beak Consultants Incorporated conducted a state of the art review of the biological impacts of minor shoreline structures on the coastal environment. The types of structures included in this study were as follows: breakwaters, jetties, groins, bulkheads, revetments, ramps, piers and other support structures, buoys and floating platforms, harbors for small craft, bridges and causeways.

A total of 555 information sources were obtained at which approximately 220 references were found by commercial bibliographic searches. Other sources were located by cross referencing from identified sources; visiting key libraries; interviewing and sending questionnaires to institutions, government agencies, and individuals who might have had useful information.

Information was extracted from the literature and compiled by type of shoreline structure and by coastal region. The following categories of information were sought: structure functions; site characteristics; geographic prevalence; engineering, socioeconomic and biological placement constraints; construction materials; expected life span; environmental conditions; methodology of environmental impact studies; physical and biological impacts; and structural and nonstructural alternatives.

Existing information was evaluated and a text was prepared (Volume I). An annotated bibliography, keyword index, and primary author reference number index were produced from the data base (Volume II).

This state of the art review summarizes and evaluates the information found in the literature for each type of structure. Areas requiring additional study are delineated. Germane studies in progress are identified, and selected case histories depicting the impacts of shoreline structures are presented as part of the review.

The impact of any structure on the coastal environment is site-specific and should be considered on a case-by-case basis. Few studies were found which quantitatively investigated the impacts of specific structures.

Structures which appear to have the greatest potential for impacting the coastal environment are small boat harbors, bridges and causeways, bulkheads, breakwaters, and jetties. Those with moderate impact potential are revetments, groins, and ramps. Low-impact potential structures include buoys and floating platforms, and piers, pilings and other support structures. Based on this classification scheme and the number and types of information sources located, bridges, causeways, and small boat harbords have received very little study relative to their potential impacts.

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INTRODUCTION

The Fish and Wildlife Coordination Act requires any public or private agency proposing activities which would control or modify the waters of any stream or body of water to consult with the U.S.Fish and Wildlife Service (FWS) "... with a view to the conservation of wildlife resources by preventing loss of and damage to such resources..."(U.S. Dept. of Interior, Fish and Wildlife Service 1975b). State and Federal legislation requires environmental impact assessments prior to construction in the coastal zone.

The U.S. Fish and Wildlife Service, charged with reviewing permit applications for construction in coastal zones, must be able to evaluate environmental impacts and suggest functionally feasible structural or nonstructural alternatives which could minimize environmental damage. Before such assessments can be made, the initial effects during structure construction,continued impact due to the presence of a structure, and cumulative perturbation due to a number of existing structures within a coastal zone must be known. Thus, it is advantageous to have a usable and comprehensive compendium of structure-related information which is specific to biogeographic regions. It is the objective of this report to summarize the known ecological impacts of minor shoreline structures and to define those areas where lack of quantitative data in the published literature makes assessment of environmental impacts difficult.

This report is the final product of a three-phase study. The objectives were

Task 1. Information Search: To develop a detailed study outline, to integrate it with FWS objectives, to obtain a comprehensive list of references and other sources of information, to secure what is immediately available, and to outline the effort required to secure the other materials.

Task 2. Information Transformation: To review the literature,to extract relevant information and to enter the data in a computer data-base.

Task 3. Information Evaluation: To analyze the biological impacts of minor shoreline structures, to identify alternatives, to describe germane studies in progress and to identify areas of insufficient research.

Each article or data source was examined within the limits set by the following outline

- Structure
- Definition
- Structure functions
- Site characteristics and environmental conditions
- Placement constraints
    - Engineering
    - Socioeconomic
    - Biological
- Construction materials
- Expected life span
- Unaltered and altered environmental conditions
- Environmental impact methodology
- Summary of physical and biological impacts
    - Construction effects
    - Chronic effects
    - Cumulative effects
- Structural and nonstructural alternatives
- Regional considerations

Types of structures included in the study are

- Breakwaters
- Jetties
- Groins
- Bulkheads
- Revetments
- Ramps
- Piers, pilings, and other support structures
- Buoys and floating platforms
- Harbors for small craft
- Bridges and causeways

The eight coastal regions selected for this study are defined as follows (Figure 1)

Coastal Region	Geographical Boundaries
1. North Pacific	Puget Sound to Monterey Bay

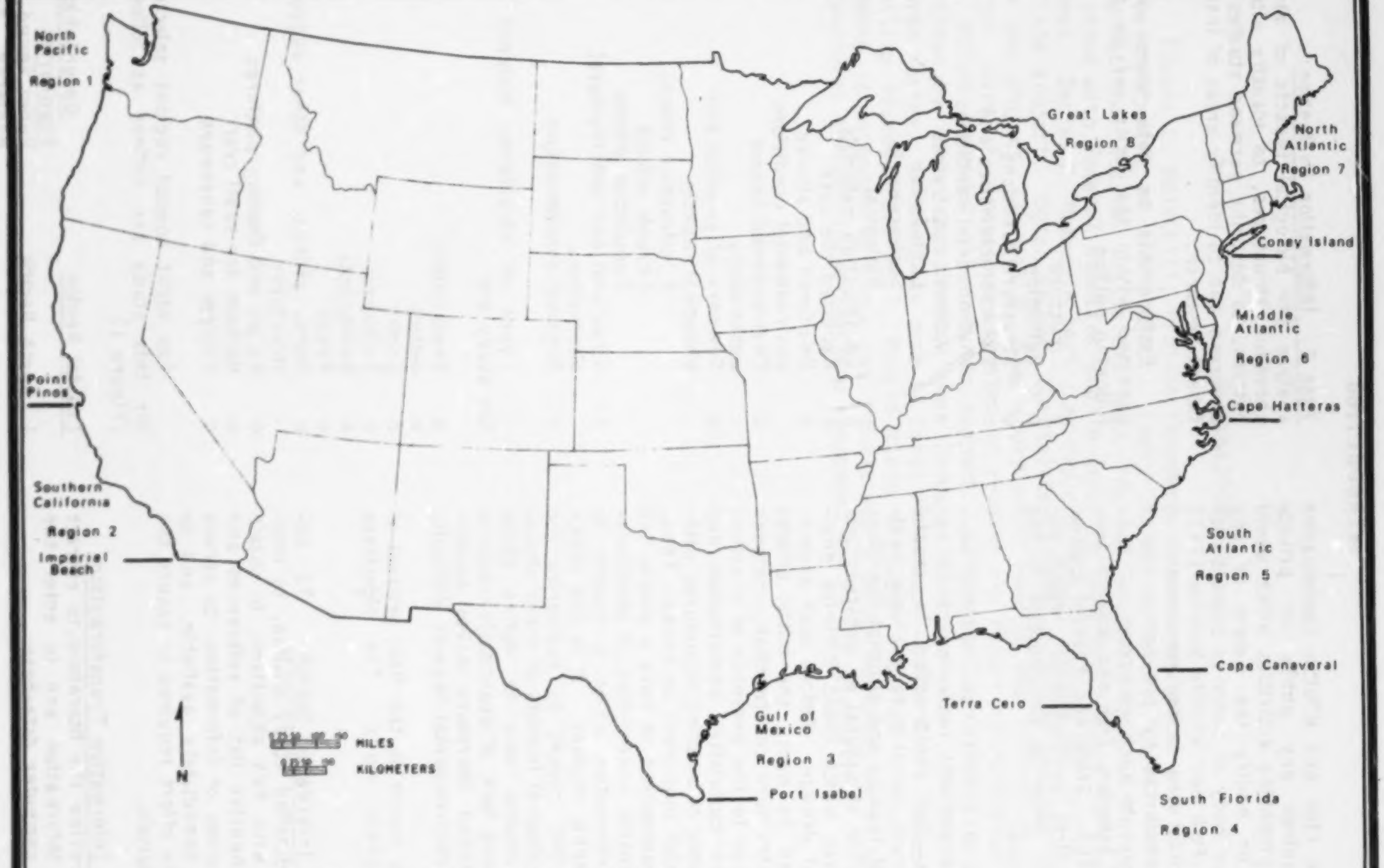
North Pacific
Region 1
Point Pinos
Southern California
Region 2
Imperial Beach
Gulf of Mexico
Region 3
Port Isabel
Terra Ceia
South Florida
Region 4
Cape Canaveral
South Atlantic
Region 5
Cape Hatteras
Middle Atlantic
Region 6
Coney Island
North Atlantic
Region 7
Great Lakes
Region 8
N
MILES
KILOMETERS

Figure 1. Coastal regions as defined in the text.

2. Southern California	Monterey Bay to San Diego Bay
3. Gulf of Mexico	Laguna Madre to Tampa Bay
4. South Florida	Tampa Bay to Banana River
5. South Atlantic	Banana River to Pamlico Sound
6. Middle Atlantic	Pamlico Sound to Coney Island
7. North Atlantic	Coney Island to Bay of Fundy
8. Great Lakes	Great Lakes

In addition to information specific to each region, this report contains a large body of data that is generally applicable to all coastal regions. Coastlines of Alaska and Hawaii were not included in the study.

Only structure-related sources of information were sought because the stated objective of this study was to provide a document that would aid in assessing environmental impacts of shoreline structures. There are numerous sources of information that are engineering or biologically related that were considered to be beyond the scope of this study. Examples would be productivity of artificial reefs or successional patterns, species composition,and productivity on submerged surfaces. Information on dredging and filling was included only where the dredging was performed to supply fill for constructing a structure. Backfilling a bulkhead would be an example. A comprehensive review on the effects of dredging is contained in Morton (1976).

The report contains a summary of the published literature and other information sources. A conscious effort was made to report only that information from the literature and not to insert the personal views of the writers of this report.

The evaluation of each structure was based on contents of the literature. Several structures had a sparse data base. A functional approach, rather than a structural approach, was taken during the study. Structures that have similar components but different functions (e.g., jetties, breakwaters, and groins) may, in many cases, have similar biological impacts. For these reasons, the entire report should be read before attempting to evaluate the impact of a specific structure.

The report is written for a professional biologist with some prior exposure to shoreline structures. It is intended to be useful during biological evaluations of applications to construct shoreline structures. The report is not intended to be a manual to assist engineers in the design of structures.

The text of this report includes a summary of the literature (organized by structure type), case history studies (arranged by coastal region),a summary of research in progress, an assessment of current environmental impact research methodologies and needs, and an evaluation of the existing data.

The text is followed by a glossary. A keyword index, a primary author reference number index, and an annotated bibliography is contained in Volume II. Entries in the annotated bibliography are alphabetized by primary author (first author when an article has multiple authors). References containing information about a specific subject or group of subjects can be obtained through the keyword index. The keywords for each reference are sorted alphabetically. Each keyword for each reference appears as the first keyword in the keyword index followed by the other keywords for that reference. This gives the user access to an article via any keyword for that article and also allows the user to combine keywords to gain access to specific classes of articles (for example, all articles with the keywords fish, revetments, and Coastal Region 1).

The primary author reference number index contains the number of the primary author of each article referred to by reference number in the keyword index. References can then be located in the annotated bibliography.

This report provides a perspective

on the state of the art for determining the biological impacts of minor shoreline structures on the coastal environment. The usefulness of the text for a specific structure is enhanced if the user consults other portions of the text for information about similar types of structures. For example, when researching boat ramps, the user should read the revetment section in addition to the ramp section. The section on piers, pilings, and support structures also should be consulted if a dock is to be constructed as part of the boat ramp facility.

The text of this report does not reproduce all of the detail contained in the literature. For this reason, the user should refer to the source documents when evaluating a specific type of structure, as well as the annotated bibliography contained in Volume II.

METHODS OF INVESTIGATION

The methods of investigation used in this study are depicted in Figure 2. Before the information search began, goals were established and a conceptual outline was created. A Procedures Manual was prepared which contained steps for information extraction and data sheet completion, as well as a conceptual outline of the project. Readers were subsequently trained, using the Procedures Manual, and their ability to extract relevant information was tested.

Concurrent with the training procedure, the search for information was begun using commercial search services, primarily through the Oceanic and Atmospheric Scientific Information System (OASIS). This system is quite inclusive of the commercial data bases that may contain information regarding minor shoreline structures. Approximately 220 of the 555 total information sources were found using the OASIS search. The balance of the information sources came from bibliographies contained in identified sources, questionnaires, libraries, and interviews.

Approximately 300 questionnaires were distributed to institutions,government agencies, and individuals that might have relevant information. A conceptual outline of the project accompanied the questionnaires. Nonrespondents and those respondents whose answers needed clarification were contacted by telephone. Where desirable,interviews and/or telephone calls were made with persons supplying valuable information in the questionnaire responses. Approximately 40 interviews were conducted. The map in Figure 3 shows the areas of the United States where questionnaires were sent and where interviews were conducted. Materials were accepted and entered into the data base until the eighth month, at which time searching was halted to facilitate timely completion of the contract report. Information was extracted from the literature and entered on data sheets by structure type and region. The information categories are contained in Figure 4. A bibliographic data sheet was also completed for each source. That sheet contained title, author, abstract, other pertinent citation information,keywords, and a rating. Articles were rated according to their applicability and usefulness to the objectives of the project (not for their scientific excellence or validity) on a scale of one (excellent) to five (poor). Those articles that were reviewed, but not considered directly applicable to the objectives of the study were abstracted, but not keyworded.

The two types of data sheets were reviewed for punctuation and spelling before being sent to keypunch. After keypunching, the data were again checked for punctuation, spelling, contents, and keypunching errors. The data were then entered into the data base (Figure 4).

The data base management system used by Beak Consultants Incorporated was System 2000 developed by MRI Systems Corporation of Austin, Texas. This system was made available through Computer Sciences Corporation's (CSC) INFONET timesharing system on the UNIVAC 1108 computer. In addition to System 2000, Beak Consultants Incorporated used its own proprietary FORTRAN programs to load the data base and provide the formatted outputs. System 2000 was used because of its ability to handle the large amount of data that were extracted from the information sources and also because of the multilevel on-line access capability which provided assistance during the report writing phase.

The outputs produced from the data base were an annotated bibliography, keyword index, primary author reference number index, and a printout of information extracted. The information was printed in a Region-Structure hierarchy although System 2000 has the capability of supplying a printout in numerous hierarchies. Data base interrogation during report writing was done through various data base entry points. Using the data outputs the existing information was evaluated and interpreted. A text was written according to the structure types and information categories presented previously in this section. An evaluation of the existing

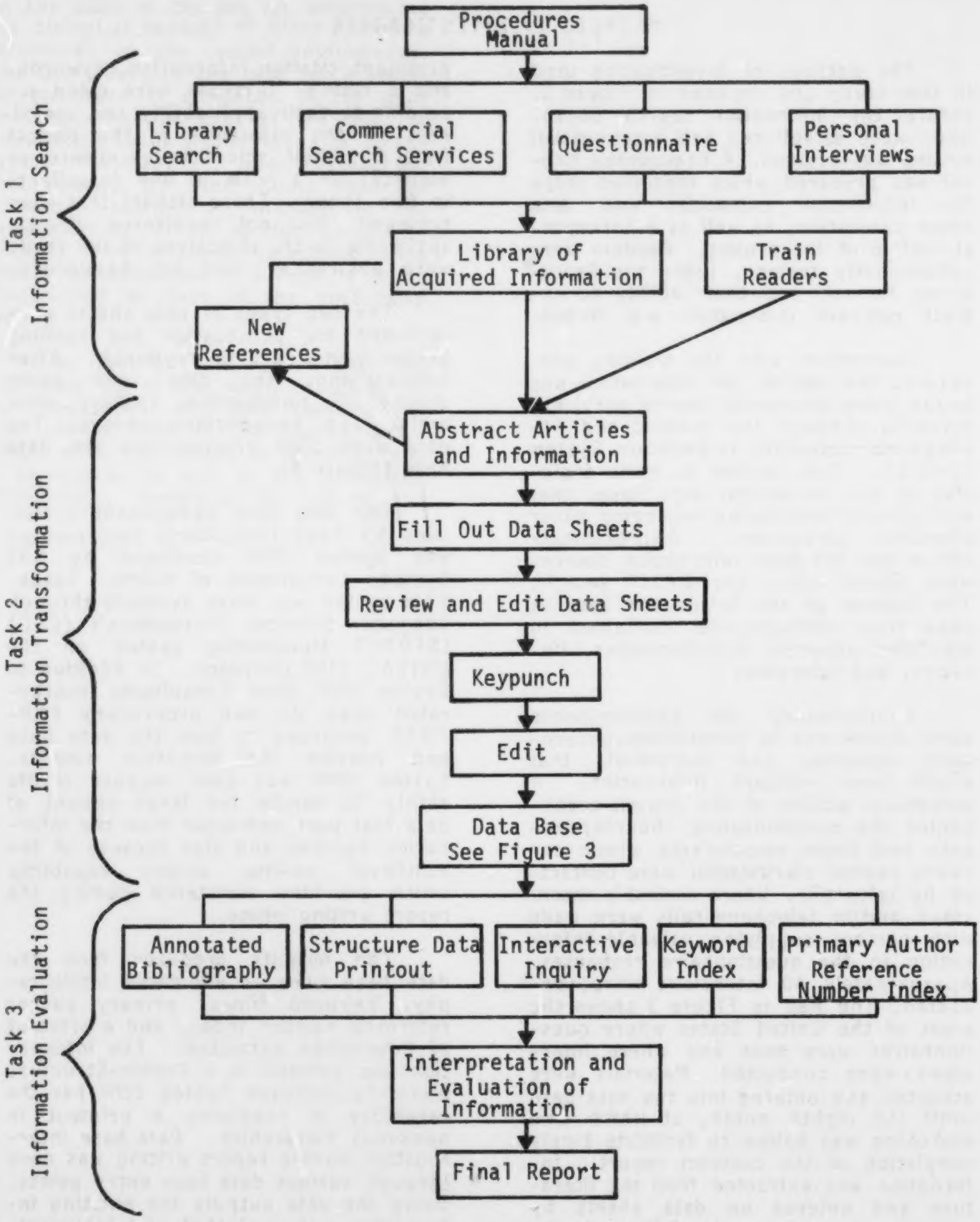
Task 1
Information Search
Task 2
Information Transformation
Task 3
Information Evaluation
Procedures Manual
Library Search
Commercial Search Services
Questionnaire
Personal Interviews
Library of Acquired Information
Train Readers
New References
Abstract Articles and Information
Fill Out Data Sheets
Review and Edit Data Sheets
Keypunch
Edit
Data Base See Figure 3
Annotated Bibliography
Structure Data Printout
Interactive Inquiry
Keyword Index
Primary Author Reference Number Index
Interpretation and Evaluation of Information
Final Report

Figure 2. Flow chart of the methods of investigation.

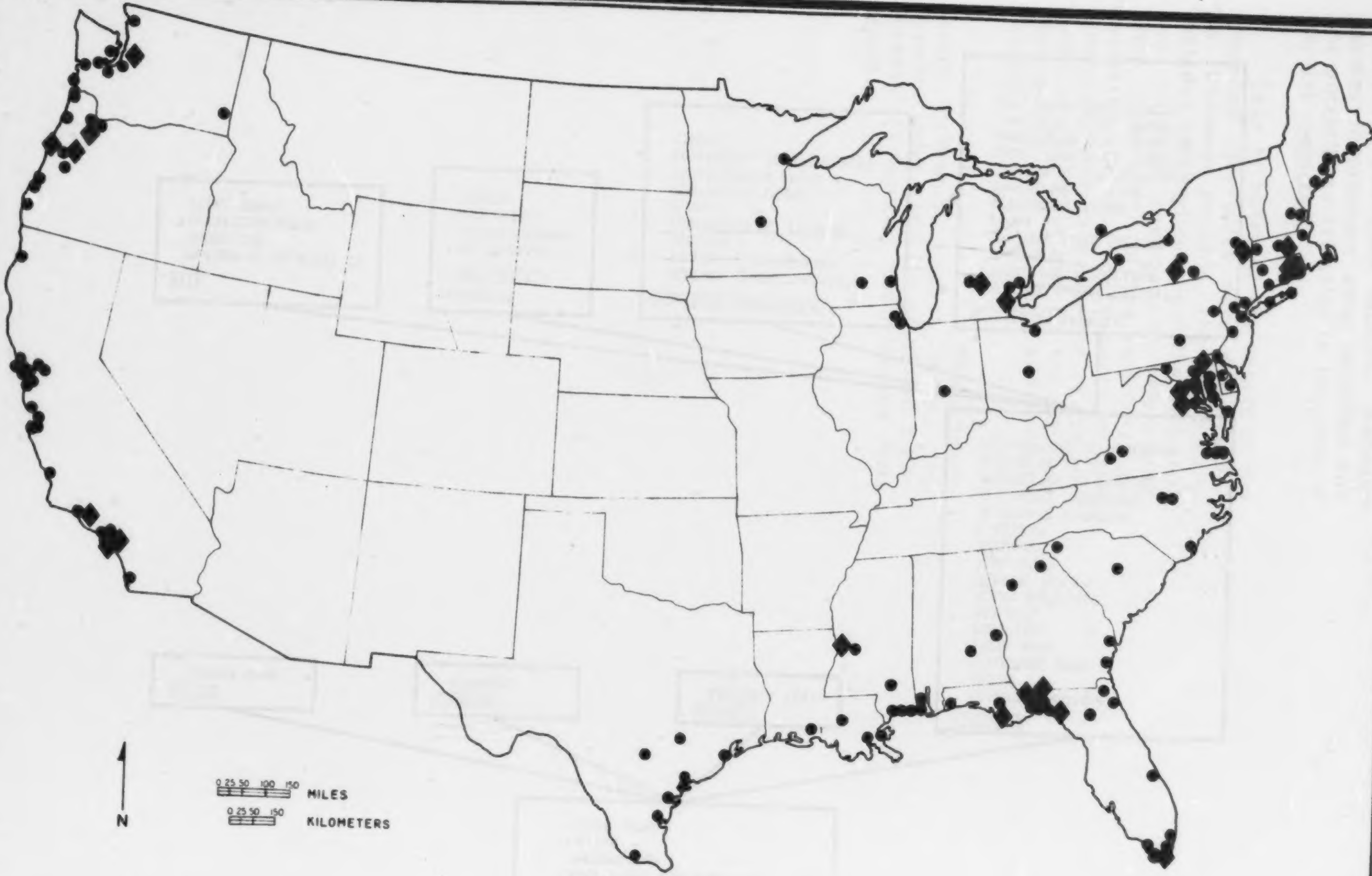
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Figure 3. Locations where questionnaires were sent and personal interviews conducted.

● Locations receiving letters and questionnaires
◆ Locations of personal interviews

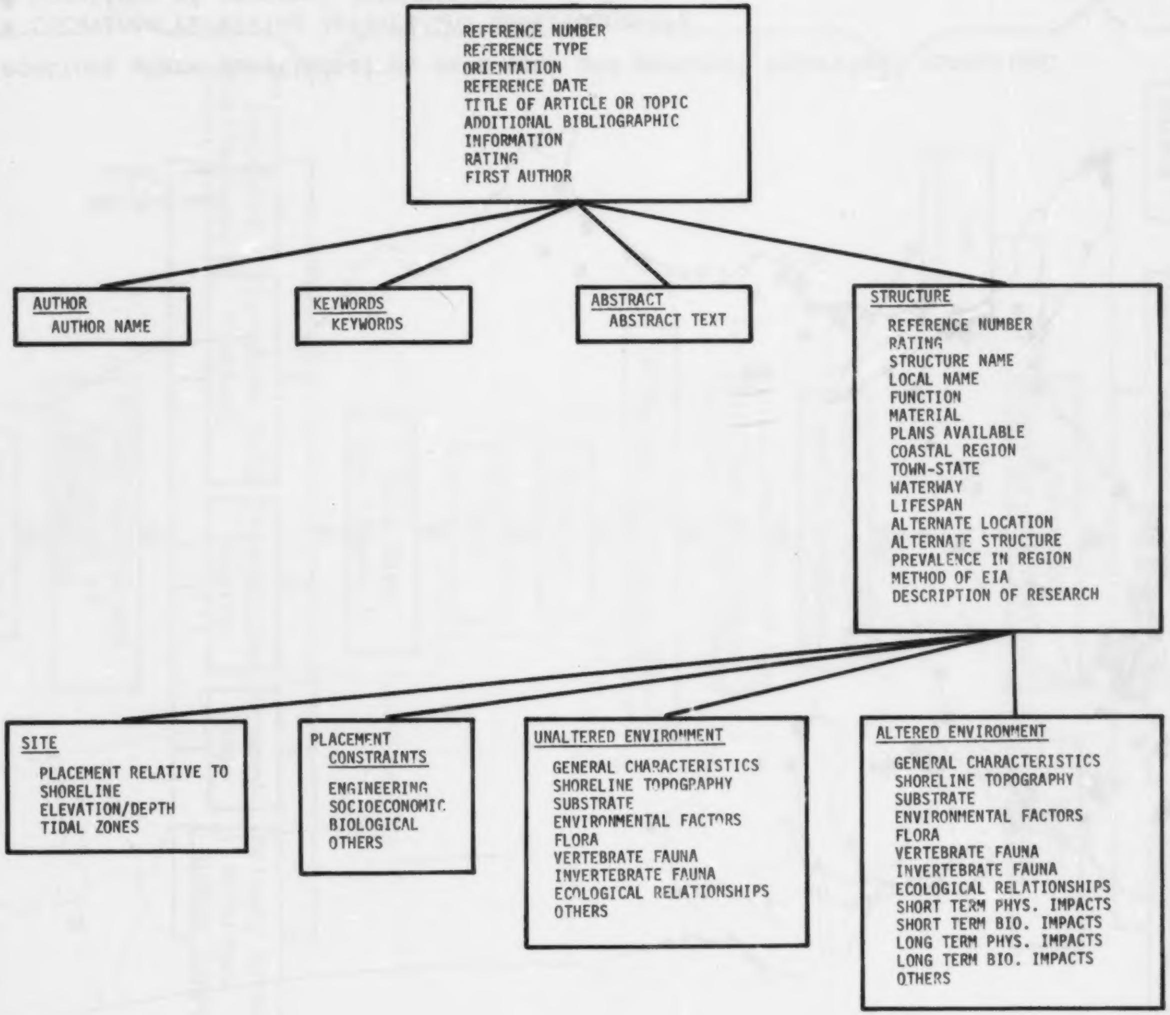

REFERENCE NUMBER
REFERENCE TYPE
ORIENTATION
REFERENCE DATE
TITLE OF ARTICLE OR TOPIC
ADDITIONAL BIBLIOGRAPHIC
INFORMATION
RATING
FIRST AUTHOR
AUTHOR
AUTHOR NAME
KEYWORDS
KEYWORDS
ABSTRACT
ABSTRACT TEXT
STRUCTURE
REFERENCE NUMBER
RATING
STRUCTURE NAME
LOCAL NAME
FUNCTION
MATERIAL
PLANS AVAILABLE
COASTAL REGION
TOWN-STATE
WATERWAY
LIFESPAN
ALTERNATE LOCATION
ALTERNATE STRUCTURE
PREVALENCE IN REGION
METHOD OF EIA
DESCRIPTION OF RESEARCH
SITE
PLACEMENT RELATIVE TO
SHORELINE
ELEVATION/DEPTH
TIDAL ZONES
PLACEMENT
CONSTRAINTS
ENGINEERING
SOCIOECONOMIC
BIOLOGICAL
OTHERS
UNALTERED ENVIRONMENT
GENERAL CHARACTERISTICS
SHORELINE TOPOGRAPHY
SUBSTRATE
ENVIRONMENTAL FACTORS
FLORA
VERTEBRATE FAUNA
INVERTEBRATE FAUNA
ECOLOGICAL RELATIONSHIPS
OTHERS
ALTERED ENVIRONMENT
GENERAL CHARACTERISTICS
SHORELINE TOPOGRAPHY
SUBSTRATE
ENVIRONMENTAL FACTORS
FLORA
VERTEBRATE FAUNA
INVERTEBRATE FAUNA
ECOLOGICAL RELATIONSHIPS
SHORT TERM PHYS. IMPACTS
SHORT TERM BIO. IMPACTS
LONG TERM PHYS. IMPACTS
LONG TERM BIO. IMPACTS
OTHERS

Figure 4. Shoreline structures data base - System 2000.

data base for each structure type was made based on the number of available references and their ratings. Germane studies in progress were identified and the potential contribution to the state of the art projected.

Case histories of the impact of the shoreline structures were also prepared. Wherever possible, the case history included information about the biological and physical environment before and after construction of the structure, an evaluation of the effectiveness of the structure, and an evaluation of the impacts of the structure on the physical environment and on fish and wildlife habitat.

The text (Volume 1), the primary author reference number index, the keyword index, and the annotated bibliography (Volume 2) comprise the final report.

SUMMARY OF LITERATURE

BREAKWATERS

Definition

A breakwater is a structure offering wave protection to a shore harbor, anchorage, or basin. Breakwaters are usually "constructed to create calm water in a harbor area, and provide protection for safe mooring, operating and handling of ships, and protection for harbor facilities" (U.S. Army Corps of Engineers 1973b).

Breakwaters may be further defined as fixed or floating, and shore-connected or detached. Fixed breakwaters are built up from the ocean, lake, or estuarine floor while floating breakwaters float at or near the water surface and are held in place by a system of tethers and anchors. Shore-connected breakwaters have a connection to existing land while detached breakwaters are not connected to the land. A detached breakwater might also be called a parallel or offshore breakwater. Shore-connected breakwaters are structurally similar to jetties, but differ in function in that their primary purpose is to reduce wave energy, not to maintain water depth. Some structures function as breakwaters and jetties.

Figure 5 is a photograph of a connected coastal breakwater which was constructed to offer protection for a natural harbor. Figure 6 is a photograph of an offshore breakwater which was constructed to create a harbor. Figure 7 contains an example of a floating breakwater.

Structure Functions

Probably the best known use of breakwaters is to create or enhance harbors for large or small craft. Normally these shore-connected breakwaters extend into a body of water to provide protection from waves caused by either wind or passing vessels. Breakwaters constructed to create a harbor may additionally protect the shoreline from erosion, alter longshore sediment transport, and support pedestrian or vehicular traffic requiring access to deeper waters of a harbor or adjacent area.

Detached breakwaters may be used to prevent or reduce wave penetration into a harbor entrance or to reduce the wave attack on a costly structure, such as a seawall or a power plant. Detached breakwaters may also be used as sand traps due to the tendency of sand to accrete on the beach in the lee of the breakwater.

Site Characteristics and Environmental Conditions

Shore-connected breakwaters often have the connected end lying perpendicular to the shoreline and the free end lying parallel to the shoreline (Figure 5). In most cases, detached, or offshore, breakwaters are parallel to the shore (Figure 6). Shore-connected breakwaters are placed according to site-specific functional requirements. Breakwaters are most commonly used to provide a sheltered harbor and, consequently, are placed where they create an area with minimum wave and surge action (U.S. Army Corps of Engineers 1973b). When associated with harbors and marinas, breakwaters usually define boundaries and provide navigation channels, as well as enclosing areas of lowered wave energy. Because their primary function is energy dissipation, breakwaters are usually placed in high-energy environments, such as coastal areas, semienclosed, or enclosed bodies of water where there is a long fetch or high occurrence of vessel-generated waves. In at least one case, however, breakwaters contributed to wave resonance and caused considerable surge within the harbor, resulting in boat damage (Slawson 1977). Breakwater placement is often determined by the existence of a shoreline area suitable for harbor facilities rather than by bottom topography, littoral processes, or other factors.

The biota of breakwater sites has apparently had little study. No generalizations can be made, based on existing data, concerning bottom characteristics, water quality, flora and fauna, or ecological interrelationships at locations where breakwaters have been planned or

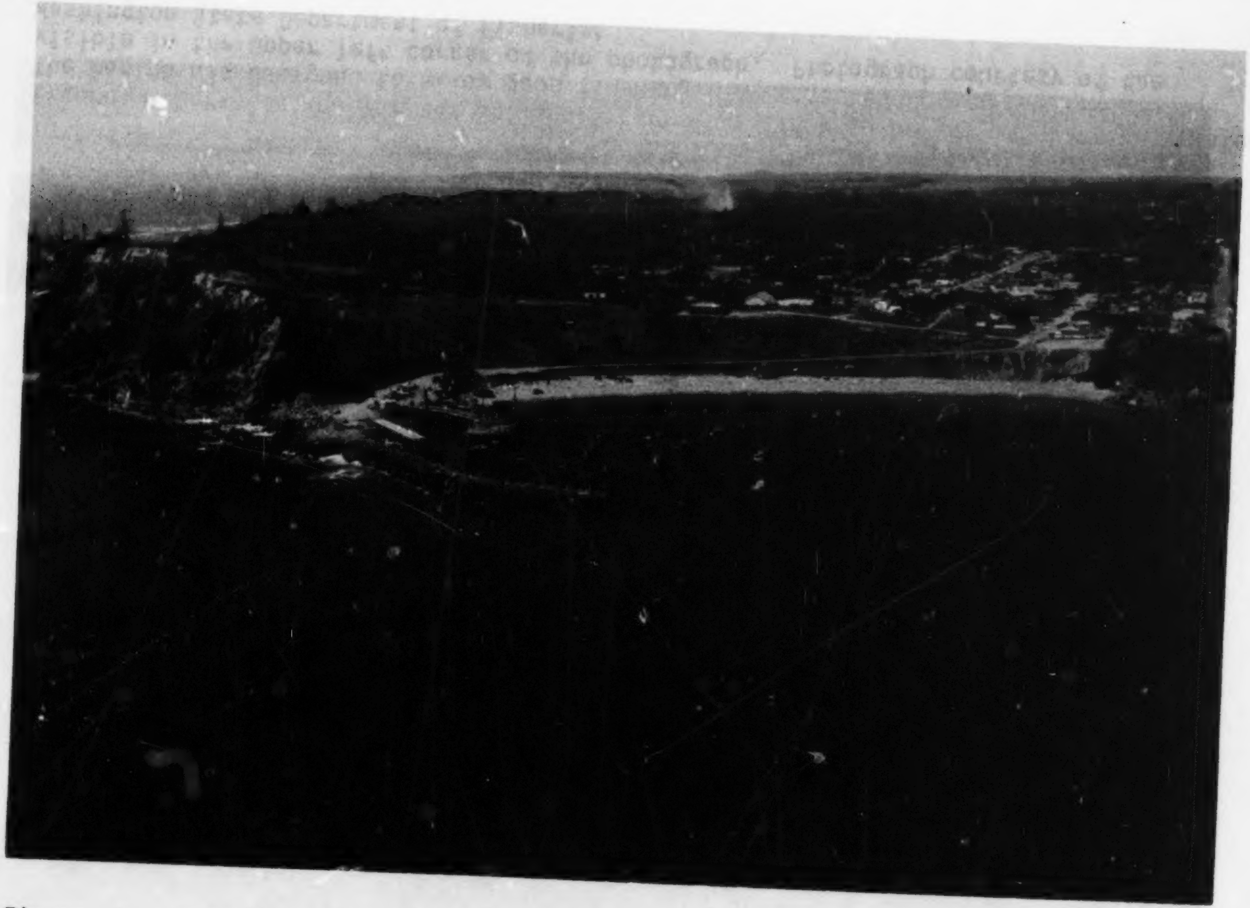


Figure 5. A small naturally protected harbor at Port Orford, Oregon is provided wave protection by a connected dogleg breakwater. Photograph courtesy of the U.S. Army Engineer District, Portland, Oregon.

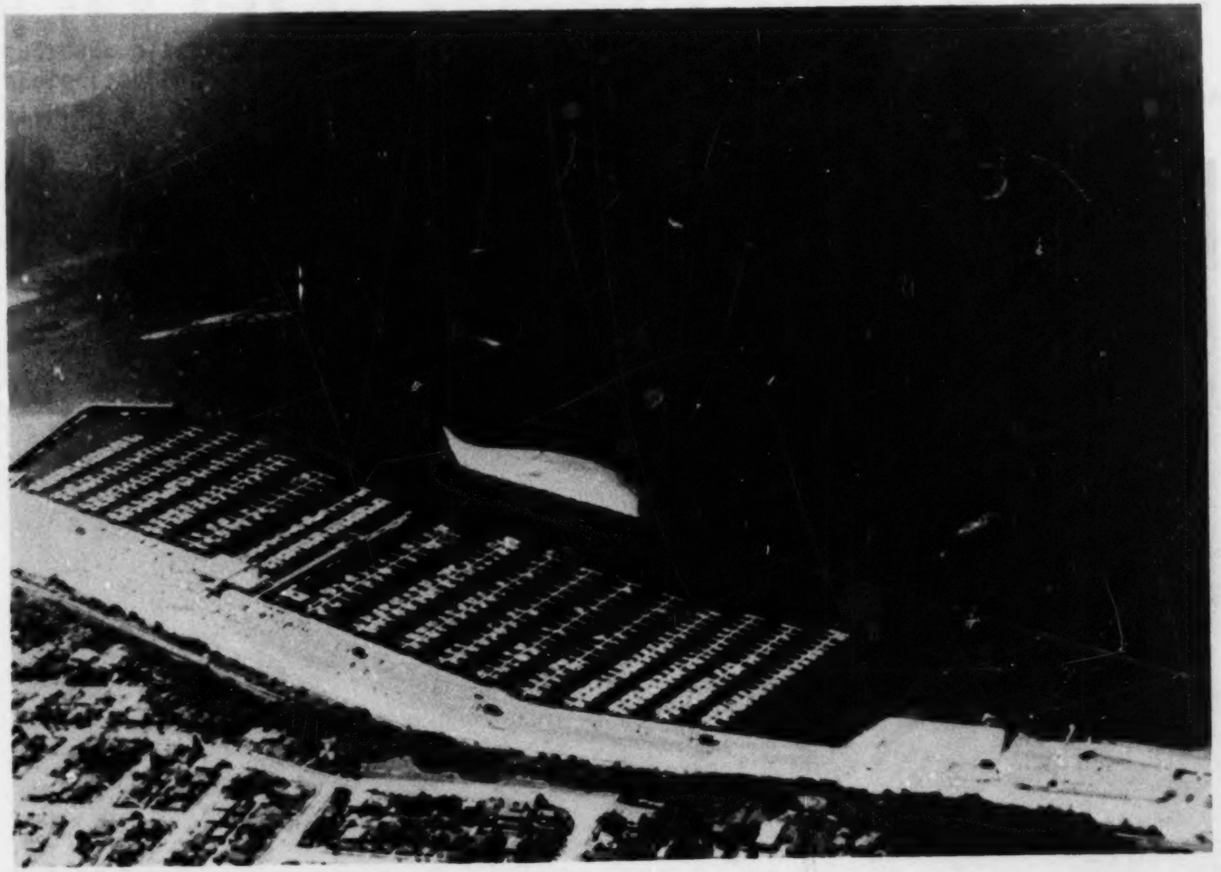


Figure 6. Protection for the Shilshole Marina is afforded by the offshore breakwater. The marina was designed to allow good flushing. An attached dogleg breakwater is visible in the upper left corner of the photograph. Photograph courtesy of the Washington State Department of Fisheries.

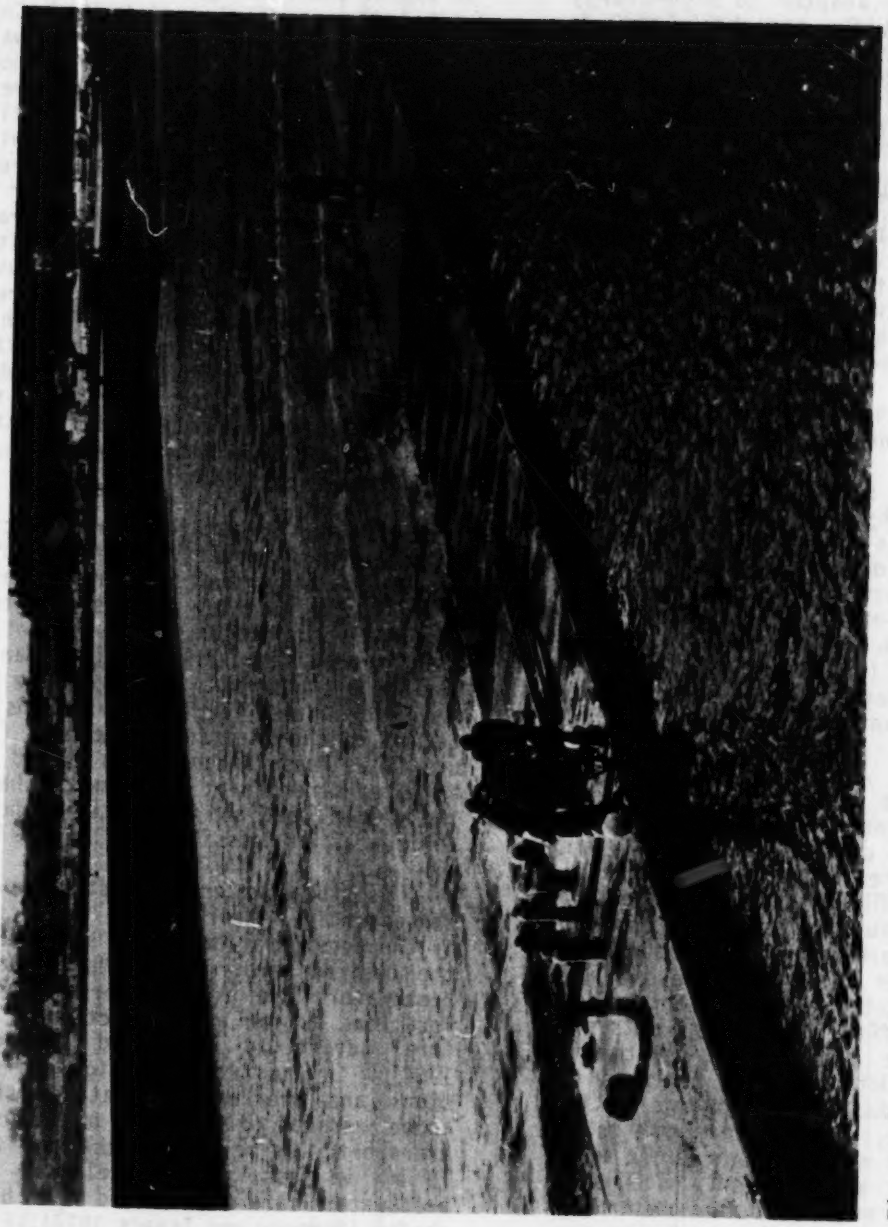


Figure 7. A floating breakwater shelters a marina in Yaquina Bay, Oregon. A navigation channel exists between the floating breakwater and the timber pile breakwater. Photograph courtesy of CH2M Hill, Inc.

constructed. Communities which occur on breakwaters are those characteristic of intertidal and subtidal rocky shores. The exposed side is often characterized by communities adapted to high-energy environments while the back side is generally inhabited by organisms typical of less hostile environments.

Placement Constraints

Engineering. Breakwater design must consider the physical environment in which the structure is to be placed, the availability and cost of construction materials, and the function of the structure. In addition to these factors, the effects of the breakwater upon its environment must be considered.

Design criteria for fixed breakwaters must consider several factors of the physical environment, including wave climate, sediment transport, bottom topography,characteristics of the protected areas, tides, and currents at the site. The design wave and the maximum wave must be determined. At this point a trade-off is often necessary between economic feasibility and failure-proof design (Saville et al. 1965). A generalized diagram of a typical rubble-mound breakwater is contained in Figure 8.

After the design wave is determined for the construction site, other factors must be considered. Studies must be made of the subtrate upon which the breakwater will rest to determine what precautions must be taken to prevent settling and erosion of foundation material (Saville et al. 1965). Prevention of erosion and settling is often accomplished by using filter blankets or mats similar to those used under revetments. This filter cloth material prolongs the settling of the breakwater stones into the substrate, which occurs due to the weight of the materials and slight movement due to wave attack. The core, cap, facing, and foundation material of the breakwater must be chosen to prevent damage or component displacement by the design wave.

Wave deflection and absorption is a primary function of breakwaters. This function is affected by the type of facing material, face slope, structure height, water depth, and wave climate at the site. A breakwater must be designed and constructed to allow breaking waves to expend their energy over a large area rather than a single point (Coen-Cagli 1932). The outer slope of a breakwater should be a low angle. The crest should reach a height which either prevents overtopping by the design wave or allows only a preplanned amount of overtopping. The design should also include provisions to prevent piling up of water behind the structure and to prevent transmitted waves from damaging facilities behind the breakwater. The required width and height of a breakwater relative to the height and wave length of the design wave are discussed by Saville et al. (1965). The conventional rubble mound or rock construction is most typical, although numerous other designs have been employed with varying degrees of success (Figure 9).

Floating breakwaters are sometimes a functional alternative to fixed structures, but they have some unique design criteria. Unless they are designed to be constantly in motion, some sort of anchor is necessary. Piles or other anchor devices are generally placed on the bottom with lines, cables, or chains attached to the floating structures (Figure 10). These anchor lines should have a tested strength at least twice that of the design load and should be as nearly horizontal as possible (Miller 1974b).

Most breakwaters protect waterways, consequently, their siting is dictated by the configuration of the shore and by the desired harbor design.Many existing breakwaters are in the worst possible locations as far as obstruction of littoral drift is concerned (Snodgrass 1964). In the future, design modifications and breakwater locations should cause minimal disruption of longshore transport. On relatively shallow, 30 ft (9 m) or less, open shorelines, fixed breakwaters are considered the better choice (Seymour and Isaacs 1974). Floating breakwaters interfere less with sand movement, water circulation, and fish habitat and are preferred for temporary installations in deep water, or where bottom conditions are unsuitable for placement of a fixed structure (Miller

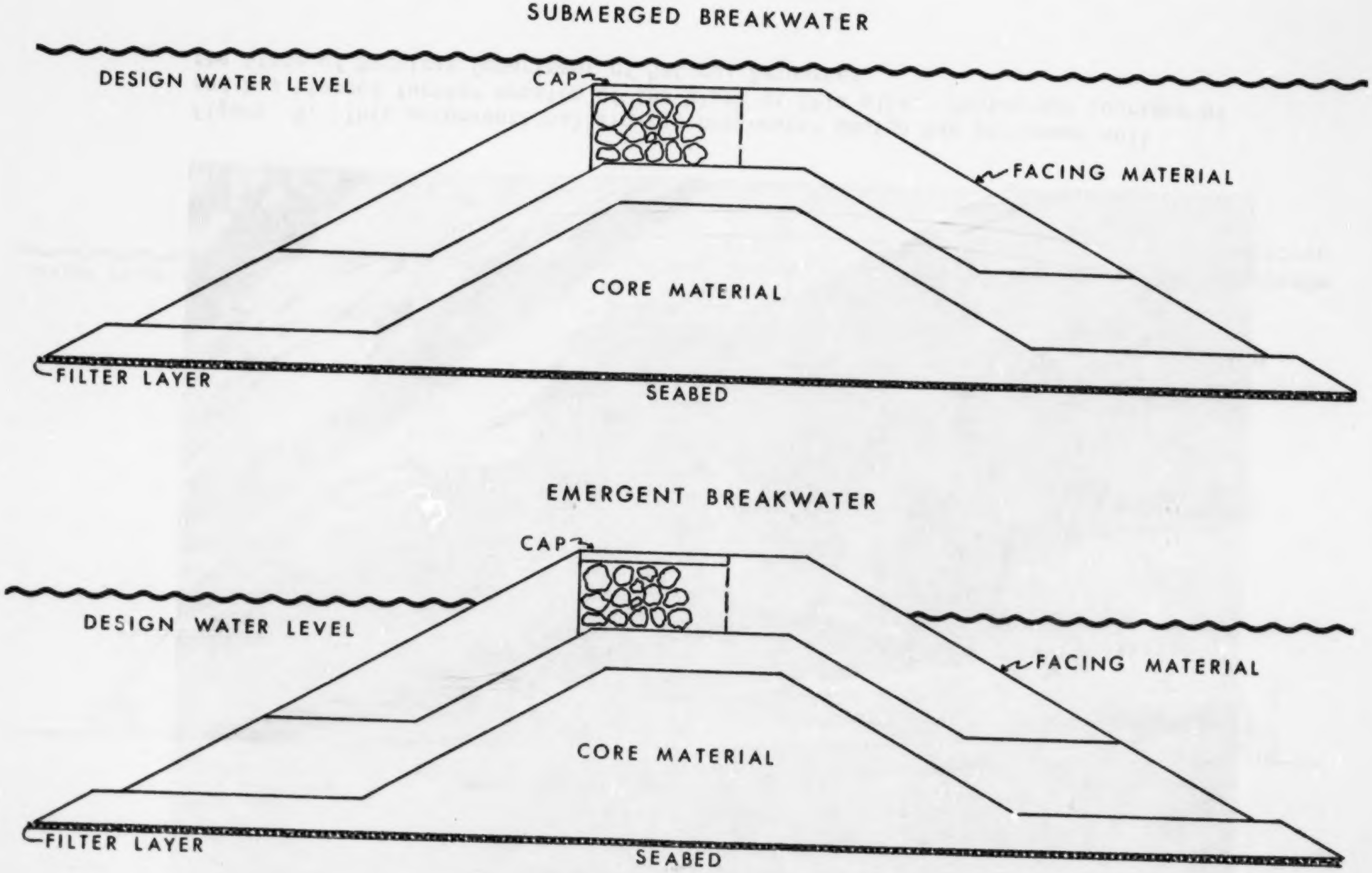

SUBMERGED BREAKWATER
DESIGN WATER LEVEL
CAP
FACING MATERIAL
CORE MATERIAL
FILTER LAYER
SEABED
EMERGENT BREAKWATER
CAP
DESIGN WATER LEVEL
FACING MATERIAL
CORE MATERIAL
FILTER LAYER
SEABED

Figure 8. Cross-sectional view of typical submerged and emergent rubble-mound breakwaters. Dimensions and details are determined by particular site conditions.

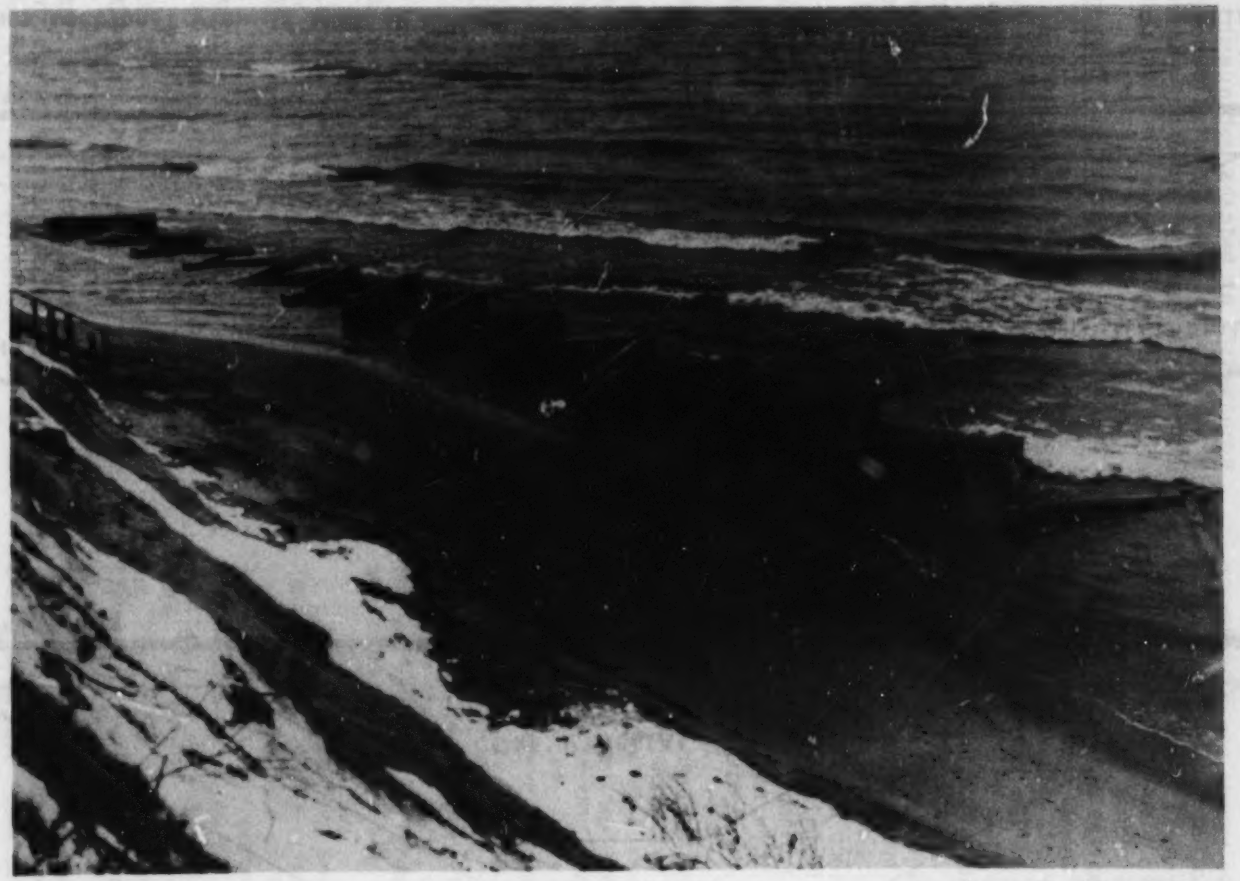
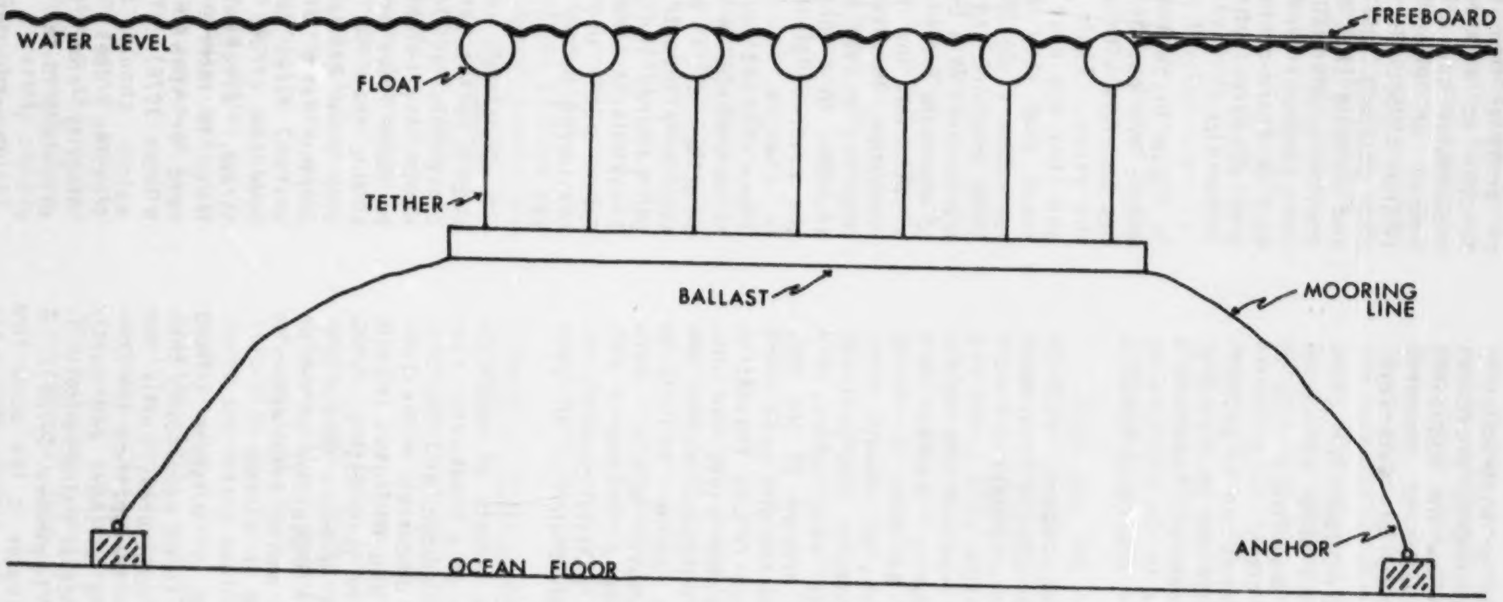


Figure 9. This unconventional zig-zag breakwater design has performed well and has stopped further erosion of the bluff at this site. Photograph courtesy of the State of Michigan, Department of Natural Resources.



WATER LEVEL
FREEBOARD
FLOAT
TETHER
BALLAST
MOORING LINE
ANCHOR
OCEAN FLOOR

Figure 10. Cross-sectional view of a tethered floating breakwater. Materials, dimensions and details are determined by particular site conditions.

1974b). If disruption or obstruction of littoral drift is unavoidable, provisions must be made to allow for bypassing sand to avoid starvation of downdrift beaches and shoaling of waterways.

Breakwaters are used for shore protection either with other structures (e.g., revetments, seawalls, groins) or as an alternative to them. Steep shorelines and sandy beaches can be protected and sand accretion can be caused or enhanced by breakwaters. Sometimes a breakwater is placed in the intertidal or subtidal zone as an erosion prevention device (Figure 9).

Maintenance requirements must be considered when choosing a breakwater design. Floating breakwaters are more vulnerable to extensive wave action and often require more frequent maintenance than fixed structures. Vertical face breakwaters must be thick or firmly braced,or high waves will damage them. Rubble mound structures can generally withstand extensive wave action, but are vulnerable to erosion at the toe, particularly at breaches and ends which can lead to a slope failure (Saville et al. 1965). Overtopping waves can dislodge cap rock. Extended storms can disarrange facing stones and cause slumping or structural failure. Submerged rubble mound structures with well-chosen facing material probably require the least maintenance of all types (Saville 1960).

The physical effects of construction and presence of a breakwater must be considered in design and location. These effects are discussed in the Summary of Physical and Biological Impacts section. Design of long-lasting, functional breakwaters is not a simple process. A thorough discussion of design criteria of rubble mound breakwaters is found in Saville et al. (1965).

Socioeconomic. Offshore fixed breakwaters tend to be more costly than shore-connected structures, partly due to the problem of transporting the construction materials offshore and partly due to the logistics of maintenance(U.S. Army Corps of Engineers 1973b). A less costly breakwater is the scrap tire artificial reef. Usually placed to provide an artificial fish habitat, it can also function as a breakwater. They are inexpensive and are considered a good method of disposing of used tires (Alfieri 1975). Floating breakwaters are also generally less expensive to build and maintain than fixed structures, but provide substantially less wave attenuation (Seymour and Isaacs 1974). The cost of shore-connected fixed breakwaters compares with that of jetties of similar size.

Low or submerged offshore breakwaters are usually unobtrusive and do not interfere with aesthetic enjoyment of the shore. Their visual impact is low, and they are usually far enough from a beach that they do not interfere with recreation (Cole 1974). In some cases, their presence can contribute to the attractiveness of a beach since they serve to attenuate incoming waves and provide a sheltered, low wave energy area for recreation. However, construction activities may hamper recreational use of the shoreline to a considerable degree, and the presence of a breakwater may lead to changes in shoreline topography. These changes could be either beneficial or detrimental to recreation. The construction of a breakwater can cause secondary impacts, such as changes in use patterns and accumulation of litter. Breakwater-associated restrictions on future public use of an area should be considered before the structure is placed.

Biological. Fixed breakwaters are subject to the same biological placement constraints as jetties, groins, revetments, and bulkheads. Riprap or dumped stone faces are biologically more desirable than flat faces since they provide more habitat for aquatic species. Sloping faces are preferable because vertical faces lack the shallow water zone and create less hard bottom substrate. Breakwaters should not be allowed to interfere with fish migratory runs or spawning areas (Persaud and Wilkins 1976). The base of the breakwaters should be protected so that scouring does not affect structural integrity and, therefore, the aquatic organisms in the area.

Construction activities should be

timed to avoid fish spawning and migration seasons, and times when birds are nesting in the vicinity of the construction site. Turbidity control devices should be employed whenever possible, and associated dredging should be minimized to avoid damage to the biota(Florida Department of Natural Resources 1973). Shellfish habitat and other areas rich in plant and animal life should be avoided. Hopper dredges seem to cause the least damage to the biota (Thompson 1973) and should be favored over hydraulic dredges. However, the use of hopper dredges is usually limited to the construction and the maintenance of entrance channels.

Construction Materials

Breakwaters can be constructed from a wide variety of materials. Generally, these can be classified as rock, wood, concrete, metal, rubber tires, filled bags, and rubber-type synthetic materials (Table 1). Almost any material possessing structural integrity could be used in breakwater construction.

The lifespan of breakwaters depends greatly on the construction materials. For this reason, preliminary material testing is necessary, both of physical characteristics and ability to withstand wave action. Tests of stone, for example,should include specific gravity, abrasion, slaking, freeze-thaw, and other relevant examinations (Allison and Savage 1976). Granites or basalts are preferable to limestone, due to the latter's tendency to abrade readily and to lose weight by dissolution of solids. If concrete is used, it should be alkali-resistant. Metals should be galvanized or coated to resist corrosion and wood should be treated with chemical preservatives. Whatever materials are used, they should be chosen on the basis of breakwater components being adaptable to substitution, ability to resist corrosion and abrasion, durability, and cost-effectiveness (U.S. Army Corps of Engineers 1973b).

The most common facing material seen on breakwaters along the United States coastlines is rubble,rough stone, or precast concrete in a variety shapes (Figures 5 and 11). The size, weight, and random or patterned placement of rubble components must be determined by individual site studies. Other facing materials include steel or concrete sheet piles, timber,and gabions, which are rock-filled wire baskets (U.S. Army Corps of Engineers 1973b). Core material is usually chosen on the basis of its permeability and whether an individual structure is designed to be permeable or impermeable. The cap, if included, is generally of rubble or precast concrete (U.S.Army Corps of Engineers 1973b).

Expected Life Span

Data are not available concerning overall life spans of breakwaters. However, periodic maintenance can be expected to prolong a structure's effectiveness. Floating breakwaters are generally not as long-lived as fixed ones. Breakwaters are constructed of materials similar to jetties; thus, some comparisons can be made concerning lifespan. Rubble mound structures, if repaired when unit displacement is severe, can last up to 50 yr (U.S. Army Engineer District, Portland 1975b). Steel, concrete, and timber structures should last up to 35 yr, depending on site-specific environmental factors (U.S. Army Corps of Engineers 1973b). Lifespan also depends on the severity of the design wave for a particular structure relative to the wave environment it will actually encounter (Saville et al. 1965).

Summary of Physical and Biological Impacts

Construction effects. Physical effects from placement of breakwaters are similar to those for jetties, groins, piers, and other structures in the nearshore areas. Rock dumping, jetting or driving piles, dredging to a solid bed or required depth, or any other construction-associated activity which disturbs the bottom sediment increases turbidity (U.S. Army Engineer District, Seattle 1971) and can impact bottom dwelling aquatic organisms, remove submerged vegetation beds, drive away fish and other mobile organisms, and alter the existing habitat at the structure site (Morton 1976, Cronin et al. 1971).

Some degree of noise, air, and

Table 1. Materials used in breakwater construction as determined from the literature.

Fixed breakwaters	Floating breakwaters
Rock	Wood
Broken quarry stone	Chemically-treated timber
Basalt	Plywood
Limestone	Concrete
Coquina	Cement reinforced with glass fiber
	Prestressed concrete
Wood	
Creosote-treated timbers	
Copper chromium arsenate-treated timbers	Metal
	Steel sheet
Chemonite-treated timbers	Steel tubing
Pentachloralphenol-treated timbers	Aluminum alloy
	Elastomeric material
Concrete	Molded polyurethane
Pour-in-place	Rubber floats
Preformed	Plastic floats
Prestressed	Fiberglass
Concrete rubble	Polystyrene
	Tires
Metal	
Steel (galvanized or coated)	
Stainless steel	
Aluminum alloy	

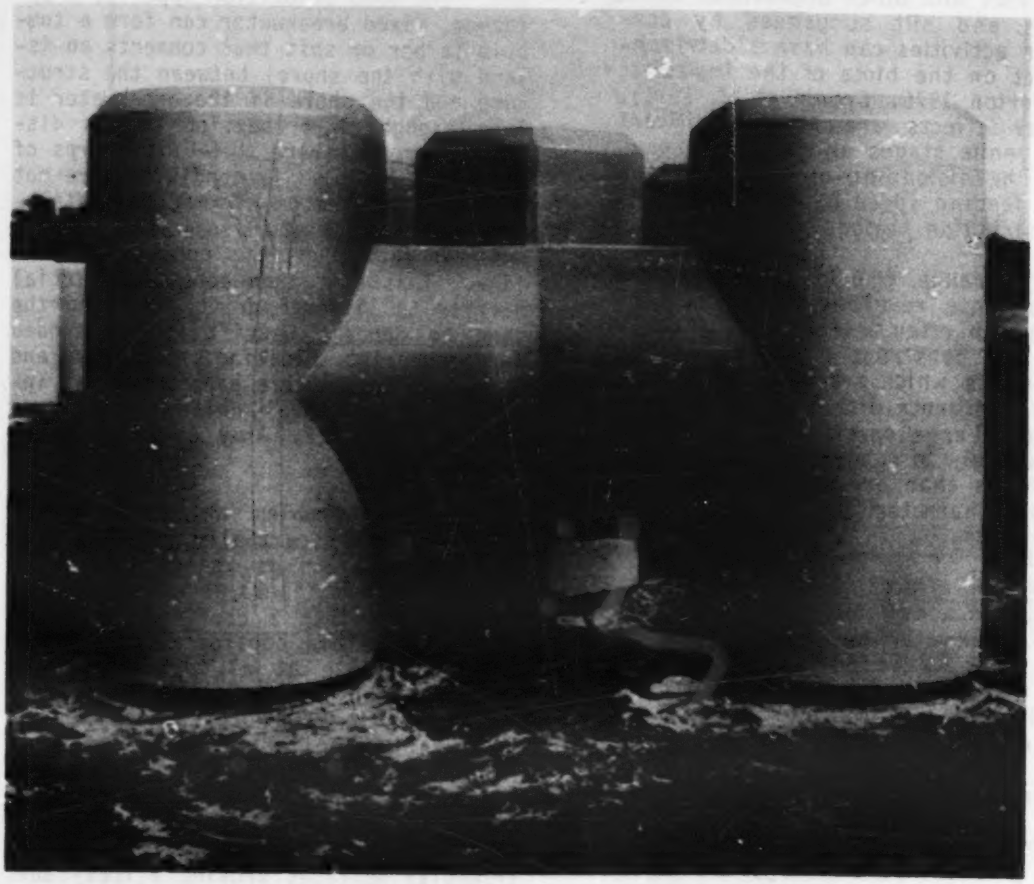


Figure 11. Tribar, a precast, reinforced concrete structure used as facing on breakwaters and jetties. Photograph courtesy Portland Cement Association.

water pollution inevitably accompanies construction activity. Petroleum products in minor quantities seep into the water from construction equipment and the exhaust emissions add hydrocarbons to the air(U.S. Army Engineer District, St. Paul 1976a). Turbidity can clog gills of fish and other organisms. Toxic materials and silt suspended by construction activities can have a detrimental effect on the biota of the immediate area (Morton 1976, Cronin et al. 1971). Turbidity effects are most significant upon juvenile stages and sessile organisms. The dislodging of organisms can cause a feeding spree by predators during construction periods.

Maintenance effects are much the same as those resulting from construction, though often less severe. Breakwaters are constructed in high-energy environments which are often characterized by sediments with fairly large particle size. Large particle-size sediments are less likely to cause turbidity or toxicity effects than are small particle-size sediments characteristic of lower energy environments.

Chronic effects. After construction is completed,a new situation exists both at the breakwater and within the protected zone. Wave energy is much reduced inside the breakwater (Ortolano and Hill 1972). A fixed breakwater can cause piling-up of water behind it, decrease circulation, interfere with tides and currents, and obstruct littoral drift (Clark 1974, Sanko 1975). If the breakwater is shore-connected, particularly if it has a shore-parallel leg, the effect on littoral drift can be severe.

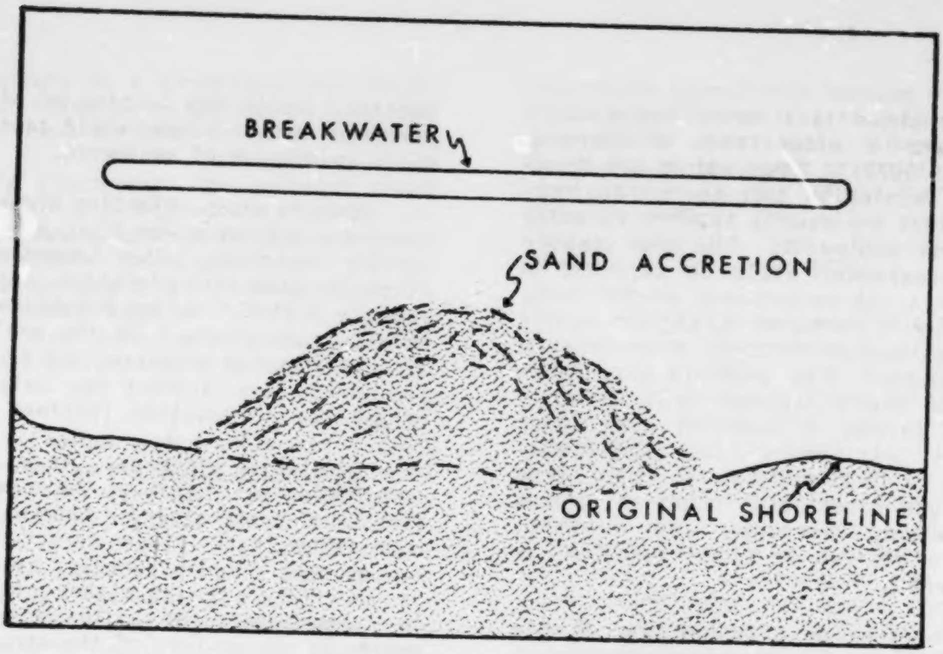
Piling-up most frequently occurs behind breakwaters that have restricted openings. This leads to a higher water level behind the breakwaters than outside (Diskin et al. 1970). Differences in the water levels result in accelerated flows at the openings or ends of a breakwater. The resultant toe scour at the base of the structure can cause both local turbidity and damage to the structure (Saville et al. 1965).

Because of lower wave energy and altered current patterns, the lee side of a fixed breakwater can experience degradation of water quality and fluctuations of temperature and salinity (Haderlie 1970). Sand tends to be deposited on the shoreline opposite a detached fixed breakwater and immediately updrift of a shore-connected structure (Figure 12). The sand deposition opposite a detached, fixed breakwater can form a tombolo (a bar or spit that connects an island with the shore) between the structure and the shore if the breakwater is long enough in proportion to its distance from the shore (U.S. Army Corps of Engineers 1973b). If conditions are not conducive to tombolo formation, detached, fixed breakwaters can still cause spit formation on the opposite shoreline. This spit then acts as a partial barrier to littoral drift, allowing the sand to deposit updrift and be eroded away downdrift. Floating breakwaters and submerged breakwaters have much less influence on littoral drift (Harris and Thomas 1974, U.S. Army Corps of Engineers 1973b).

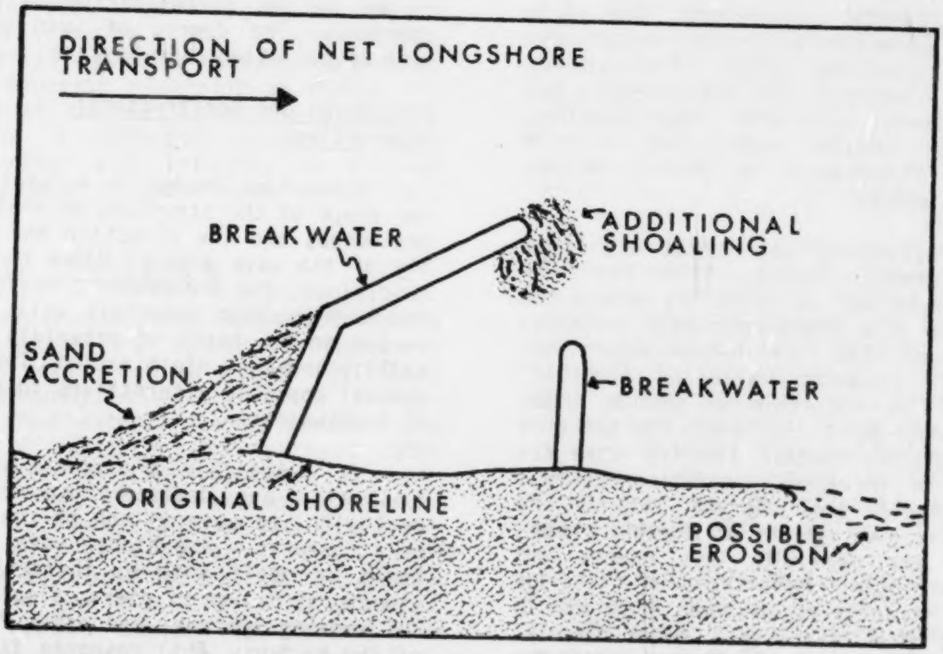
Another problem which can occur within a harbor partially enclosed with fixed breakwaters is the generation of secondary waves. These waves result from reflection within a confined space and can often attain considerable size and energy (Saville et al. 1965). Careful design will usually prevent this situation; but if it occurs, alterations in the existing facilities become necessary (Slawson 1977).

Breakwaters constructed from the rock, rubble, and other materials with irregular surfaces provide a rocky surf habitat on the seaward side,and a rocky calm habitat on the lee side (Kowalski and Ross 1975). These new habitats are gained at the cost of the previously existing bottom dwelling organisms. In many situations, the new rocky habitat can be considerably more productive than substrate that previously existed. This is well documented in literature about artificial reefs.

The protected water inside a fixed breakwater, with the possible altered fluctuations of temperature, salinity, and water level, can lead to a change in the plant and animal species composition


BREAKWATER
SAND ACCRETION
ORIGINAL SHORELINE

DETACHED EMERGENT BREAKWATER


DIRECTION OF NET LONGSHORE TRANSPORT
BREAKWATER
ADDITIONAL SHOALING
SAND ACCRETION
BREAKWATER
ORIGINAL SHORELINE
POSSIBLE EROSION

ATTACHED BREAKWATER

Figure 12. The dotted lines show typical areas of erosion and sand accumulation behind attached dogleg and detached solid breakwaters. The sand formation behind the offshore breakwater is called a tombolo.

with sensitive taxa being replaced by those with a wider range of tolerance (Gifford 1977). Breakwaters are functionally located in high-energy environments that are usually typified by rather coarse sediments. The area seaward of a breakwater would be expected to develop a coarse-sediment environment, especially if compared to the previously existing deeper bottom, a low-energy environment. The enclosed area landward of the breakwater will, in many cases, develop a sediment composition that is less coarse than previously existed. This shift in sediment type will cause concomitant shifts in species distribution, diversity, and numbers. These shifts can be either beneficial or detrimental.

The creation of a new type of bottom often results in replacement of a deepwater fish habitat with a shallow shellfish habitat (Snow 1977). This will depend upon the biology of the area where the breakwater is constructed. If sand deposition creates an emergent or intertidal sandbar, then a new type of bird habitat may result. The stone surface upon and behind the breakwater may be used by birds. The sandbar and rock habitats are preferred by the gulls, terns, and other beach-dwelling species. Colonial nesting may occur if human disturbance is limited during nesting season.

Breakwaters can affect longshore fish migration routes. This has been documented for salmonid fry where the presence of a shore-connected breakwater forced them into deeper water than previous conditions afforded (Stockley 1974). The reduction of shallow water areas decreased the available salmonid fry migration routes. The fry were exposed to increased predation because they would not migrate around the structure. The effects of floating breakwaters are generally less severe and the Washington Department of Fisheries (1971) strongly recommends their use to protect fish resources. Water circulation is only slightly affected, and the piling-up of water behind the floating breakwaters is negligible because they are anchored by cables or widely spaced piles (Kowalski 1974b). Installation causes much less disturbance of bottom habitat, though any setting of piles or permanent anchor blocks would cause some minor suspension of sediments.

Once in place, floating breakwaters provide a substrate for fish, algae, and sessile organisms. They interfere only minimally with fish migration. By shading the bottom, floating breakwaters can reduce productivity, but the proliferation of attached organisms and the grazers which they attract may balance or offset their reduction (Gifford 1977).

Cumulative effects. Very little information was found on the cumulative effects of breakwaters or breakwaters in combination with other structures. If two or more fixed structures are placed in proximity, the resultant alteration in current patterns could cause scour damage to one or more of the structures. The location of structures close to each other can cause other synergistic effects: littoral transport modifications, alterations of wave energy environments, and alterations of water quality parameters, such as salinity and dissolved oxygen or the concentration of petrochemicals. The degree of such changes must be evaluated case-by-case.

Structural and Nonstructural Alternatives

Breakwater design is a function of the shape of the structure or area to be protected, and the direction and severity of the wave attack. Given these two conditions, the breakwater cross-section and construction materials will be selected on the basis of materials availability and cost minimization. There are several possible alternatives to proposed breakwaters.

It is possible to dispense with the breakwater and devise other means to deal with the wave attack on the harbor or structures. The higher wave climate could be dealt with by increasing the structural design of piers, floats, vessel mooring systems, and other features of the harbor. This response is generally more feasible in harbors for large ships because small craft cannot take repeated pounding against structures.

If the shoreline must be protected,

alternatives to a breakwater are revetments, seawalls, bulkheads, increased beach cross-section, or other methods.

To compensate for reduced water circulation and attendant problems inside a basin protected by a breakwater, a permeable breakwater or floating breakwater could be substituted for a fixed, solid structure. Floating breakwaters have the additional advantage of being portable and, to some extent, reusable.

In shallow water areas not subject to severe wave attack, vertical wood pile or sheet pile structures are often used as breakwaters. If rock is available, a low, rubble mound structure may prove equally effective and economical, while alleviating some of the environmental problems associated with fixed breakwaters and vertical surfaces.

When the breakwaters are used to create a basin, there is usually a shape that will minimize the total cost and reduce the dredging required for the basin. Placing the basin in deeper water may increase breakwater costs, but decrease dredging costs. The reverse is also true. Assuming there is no problem with property ownership or rights, the shape of the basin can be altered to achieve a different balance between breakwater and dredging or between development of water area versus land area.

Regional Considerations

Breakwaters are found at virtually every harbor and estuary on the north Pacific coast (Coastal Region 1). They are primarily intended to protect waterways from extensive wave action. The State of Washington has outlined strict guidelines for their design and placement. These include the following physical placement criteria: at least two gaps must be provided to allow water circulation and flushing; the structures must be less than 250 ft (69 m) from MHHW (mean higher high water) line and not be below 0 ft MLLW (mean lower low water); facings must be permanent material and stair-step design; the openings must not be shallower than the dredged enclosure. Vertical faces are considered undesirable because they preclude a shallow water area, while 30-degree slopes approximate natural conditions.Though raw earth or gravel facings are similar to the normal habitat of juvenile salmon, they allow erosion and damage shellfish beds (Washington Department of Fisheries 1971).

Limited data are available concerning altered environmental conditions. Algae and hydroids have been noted on breakwaters in Puget Sound (Millikan et al. 1974, Smith 1976) and fish were abundant at one breakwater (Smith 1976). Smith (1976) also reported three distinct zones of marine invertebrates along a breakwater. Rigg and Miller (1949) observed surf habitats on the outer face of a breakwater and typical quiet water types of sessile organisms on the inner face. They also observed an unexplained abundance of starfish at one breakwater. Millikan et al. (1974) noted large amounts of herring spawn on evergreens submerged in the vicinity of breakwaters; flocks of scoters fed heavily upon the spawn.

Physical impacts, as described in the general section,were expected to result from the construction and presence of breakwaters on the north Pacific coast (Coastal Region 1). The major biological impact discussed was upon salmonid fry which became vulnerable to predation due to an interference with migration (Richey 1971). In some cases shellfish beds were destroyed by breakwater placement, but in others new clam beds were established in sand accretion areas. Shoaling around one breakwater was expected to alter benthic habitat, preclude bottom use by fish and shellfish, and create additional bird habitat (U.S. Army Engineer District, Seattle 1971). However, Rigg and Miller (1949) reported that another breakwater in Puget Sound had no noticeable effect on organisms in its vicinity after 10 yr.

Most of the breakwaters in southern California (Coastal Region 2) are associated with harbors,often small boat moorages. In a few cases, detached offshore breakwaters function as shore protection structures. Both shore-connected and detached breakwaters can be found in this region, and most of these are constructed of rubble mound. Physical impacts from breakwater construction and presence are similar to those previously described. Deterioration of water quality is frequently a problem in breakwater protected harbors (Slawson 1977, Carlisle 1977). Red tides (dinoflagellate blooms) are severe in most harbors in the Los Angeles-Long Beach area (Slawson 1977) and probably occur frequently wherever circulation is impaired.

Breakwaters in the Gulf of Mexico (Coastal Region 3) are used both for shore protection and in harbor areas. They are placed either parallel or perpendicular to the shoreline. Most act as littoral drift barriers and require modifications to bypass sand. Construction materials are rock, concrete, sheet piling, timber, and scrap tires. Scrap tire breakwaters are being developed for protection of the Florida coastline (McAllister 1977).

Breakwaters are less common than groins in south Florida (Coastal Region 4). Most of the existing ones are part of small boat harbors. A large portion of south Florida is characterized by natural offshore reefs and is also somewhat protected by the Bahamas (McAllister 1977). Floating breakwaters often attract marine animals and is one case a community of marine invertebrates and fish was well established on a floating breakwater within a month of its placement (Gifford 1977).

No unique information concerning breakwaters in the south Atlantic (Coastal Region 5) was found. Physical and biological impacts were similar to those desribed for other regions.

Sandbag sills (sand-filled nylon tubes or lines of sandbags) were the only type of breakwater for which information unique to the middle Atlantic (Coastal Region 6) was found. These are utilized to prevent erosion of individual waterfront lots or to improve the effectiveness of a groin system. They are placed much farther inshore than most breakwaters and are considerably smaller than the usual breakwater. Placement is in the subtidal zone, just below mean low water, on sand beaches with complex patterns of littoral transport. Physical and biological impacts are expected to be insignificant though no quantitative studies have been made. Unless well marked, they may be a navigation hazard to small craft at low tide.

Little information was found concerning breakwaters in the north Atlantic (Coastal Region 7).

Breakwaters are frequently used in the Great Lakes (Coastal Region 8) for shore and harbor protection. Most are shore-parallel and detached. Construction materials include many of those listed in Table 1. One rather unusual design is that of a steel or concrete zig-zag wall parallel to shore with its crest just above mean water level (Figure 9). One physical impact of breakwaters which is unique to the Great Lakes is the enhancement and prolonging of harbor icing. Protected water behind breakwaters ices over earlier in the fall (U.S. Army Engineer District, Buffalo 1975a) and remains frozen longer in the spring.

JETTIES

Definition

"A jetty is a structure extending into the water to direct and confine river or tidal flow into a channel and to prevent or reduce shoaling of the channel by littoral material. Jetties, located at the entrance to a bay or river, also serve to protect the entrance channel from wave action and cross currents. When located at inlets through barrier beaches, they also stabilize the inlet locations." (U.S. Army Corps of Engineers 1973b).

The most common type of jetty is one extending into the ocean at the entrance to a bay or river (Figure 13). However, training works (including training walls) located in estuaries and along rivers to guide currents and assist in channel deepening are also commonly called jetties. Sometimes a structure placed in a river or on an estuarine beach to direct currents and stabilize the beach is called a jetty or a groin (see Glossary).

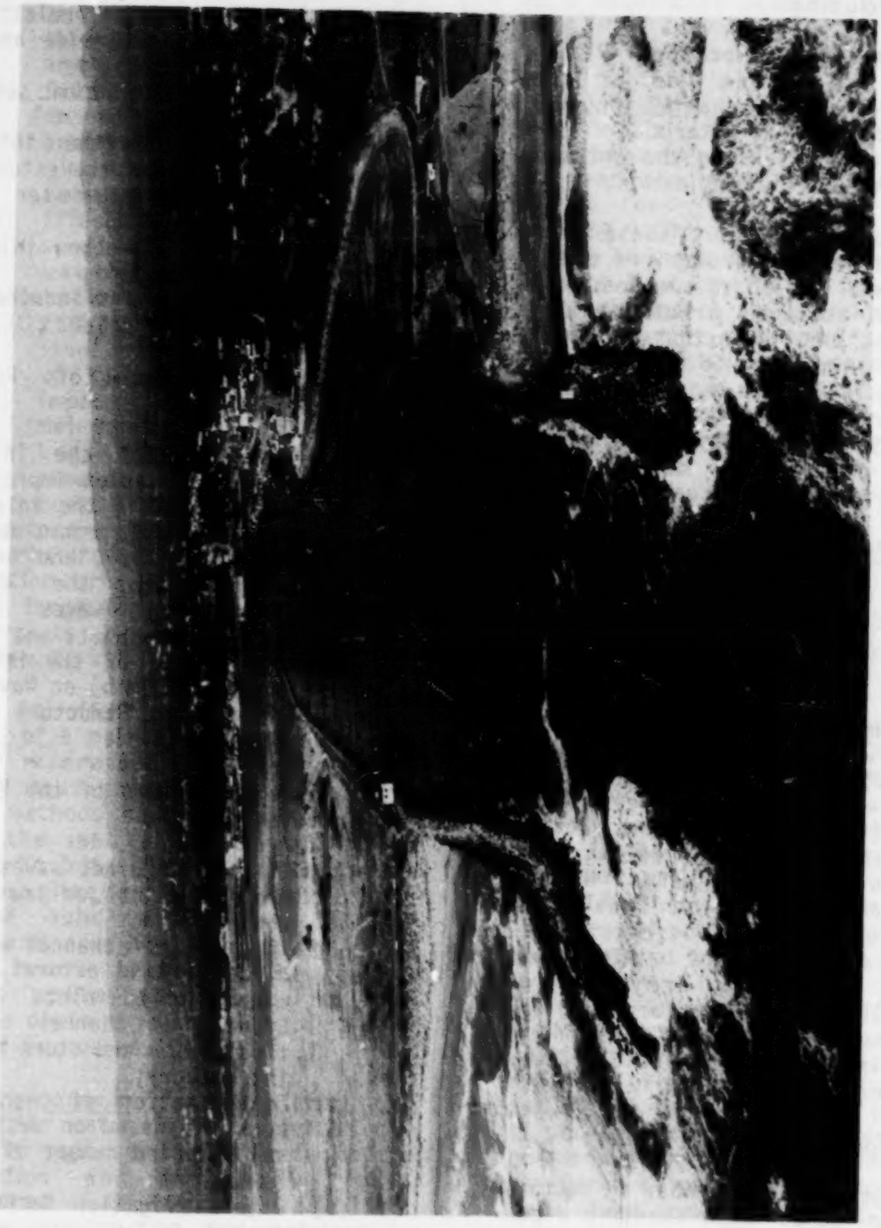


Figure 13. Jetties at mouth of Coquille River, Bandon, Oregon. Photograph courtesy of U.S. Army Engineer District, Portland, Oregon.

Structure Functions

Jetties located at coastal entrances to bays or rivers usually have multiple purposes, including:

- stabilize the inlet location;
- direct and confine flow or prevent or reduce channel shoaling from littoral drift material;
- protect vessels using the entrance from wave or current action.

When taken together, these functions have aspects of groins and breakwaters, as well as jetties. Jetties located inside of estuaries or along rivers may have the single function of directing and confining flow to reduce channel shoaling. Sometimes, these structures concurrently function as groins because they may stabilize or otherwise change the movement of material along an estuarine or riverine beach.

Site Characteristics and Environment Conditions

Jetties are usually placed on one or both sides of an inlet, extending from above high water on the shoreline but beyond low water (Ortolano and Hill 1972). They sometimes extend out to the depth of the associated navigation channel (U.S. Army Corps of Engineers 1971b) and usually extend beyond the surf zone (Gifford 1977). Most jetties are found at river or bay openings into the ocean or the Great Lakes. Natural and man-made inlets, when unaltered, usually interrupt the longshore movement of sand. This causes bar formation in the inlet mouth (U.S. Army Corps of Engineers 1971b). Jetties are also located at natural and man-made inlets through barrier beaches (U.S. Army Corps of Engineers 1973b).

Placement Constraints

Engineering. A number of factors must be considered when choosing a design and a site for a jetty. The Shore Protection Manual (U.S. Army Corps of Engineers 1973b) recommends careful study of the following:

"a. Hydraulic Factors of the Existing Inlet.

(1) The tidal prism and cross-section of the gorge in the natural state;
(2) Historical changes in inlet position and dimensions..;
(3) Range and time relationship (lag) of tide inside and outside the inlet;
(4) Influence of storm surge or wind setup on the inlet;
(5) Influence of the inlet on tidal prism of the estuary and effects of freshwater inflow on the estuary;
(6) Influence of other inlets on the estuary; and
(7) Tidal and wind-induced currents in the inlet.

b. Hydraulic Factors of Proposed Improved Inlet.

(1) Dimensions of the inlet...;
(2) Effects of inlet improvements on currents in the inlet, and on the tidal prism, salinity in the estuary, and on other inlets into the estuary;
(3) Effects of waves passing through the inlet; and
(4) Interaction of the Hydraulic Factors (item b) on Navigation and Control Structure Factors (item c and d).

c. Navigation Factors of the Proposed Improved Inlet.

(1) Effects of wind, waves, tides and currents on navigation channels;
(2) Alignment of channel with redirection and natural channel of unimproved inlet;
(3) Effects of channel on tide, tidal prism and storm surge of the estuary;
(4) Determination of channel dimensions based on design vessel data and number of traffic lanes; and
(5) Other navigation factors such as:
    (a) Relocation of navigation channel to alternate site;
    (b) Provision for future expansion of channel dimensions; and

(c) Effects of harbor facilities and layout on channel alignment.

d. Control Structure Factors.
   (1) Determination of jetty length and spacing by considering the navigation, hydraulic, and sedimentation factors;
   (2) Determination of the design wave for structural stability and wave runup and overtopping considering structural damage and maintenance; and
   (3) Effects of crest elevation and structure permeability on waves in channel.

e. Sedimentation Factors.
   (1) Effects of both net and gross longshore transport on method of sand bypassing, size of impoundment area, and channel maintenance; and
   (2) Legal aspects of impoundment area abd sabd bypassing process.

f. Maintenance Factor. Dredging will be required,especially if the cross-section area between the jetties is too large to be maintained by the currents associated with the tidal prism."

To be effective in preventing the shoaling of a navigation channel, jetties must be impermeable. However, impermeability causes downdrift sand starvation so methods have been developed to bypass the sand which accretes behind the updrift jetty. These include bypass pumping, placement of the weirs in an otherwise solid jetty, sand transfer plants, and dredging. Dredging is also used to remove bars which form in the channels lacking adequate currents to maintain depth by scour (U.S. Army Corps of Engineers 1973b).

Socioeconomic. The size, type, and construction materials of the jetties depends, in part, on available funds for construction and maintenance (U.S. Army Corps of Engineers 1973b). Neither the construction nor maintenance should severely hamper commercial or recreational use of the area around the jetty site (Persaud and Wilkins 1976). It is also important to consider the final appearance of a jetty, either alone or as part of the overall shoreline scene (Snow 1973). Jetties provide a spot for fishing, and safe passage to and from a harbor for small craft. In addition, during the construction period there may be a beneficial economic effect in the area (U.S. Army Engineer District, Portland 1976e).

Biological. When planning jetty construction, the effects of the structure on area wildlife propagation and movement should be considered (Coastal Plains Center for Marine Development Service 1973). Migratory runs of fish may be affected by changes in an inlet. Construction activities should be carefully planned to avoid fish migration or spawning runs (Persaud and Wilkins 1976). Dredging to bypass or remove accumulated sand should also be scheduled for times of relatively low productivity (Thompson 1973). Care should be taken in the choice of downdrift sand release sites to avoid movement of sand onto productive fish and shellfish areas or rich plant communities (Cronin et al. 1969). If the accumulated sand is not returned to the littoral drift, it should be disposed of carefully.

Construction Materials

Jetties along the United States coastlines are usually built of rubble or quarried stone (U.S. Army Corps of Engineers 1973b). Other materials occasionally used, particularly in the Great Lakes, are steel sheet pile cells, cassions, and timber, steel, or concrete cribs. Prefabricated concrete components (Figure 14) are sometimes used on the outer layer.

Caps on rubble mound jetties are often concrete embedded with large stone. Thick bedding layers of gravel or stone often extend out from the facing layer affording the toe of the structure protection from scour. Medium-sized stone is usually placed between the large stone or shaped concrete facing. Most cribs, cassions, and sheet pile cells are filled with dredged material, gravel, or small-sized quarry stone and capped with concrete or large-sized cover stones lying on a bedding layer. A stone mattress and riprap are usually placed at the base of the vertical walls. These toe structures have

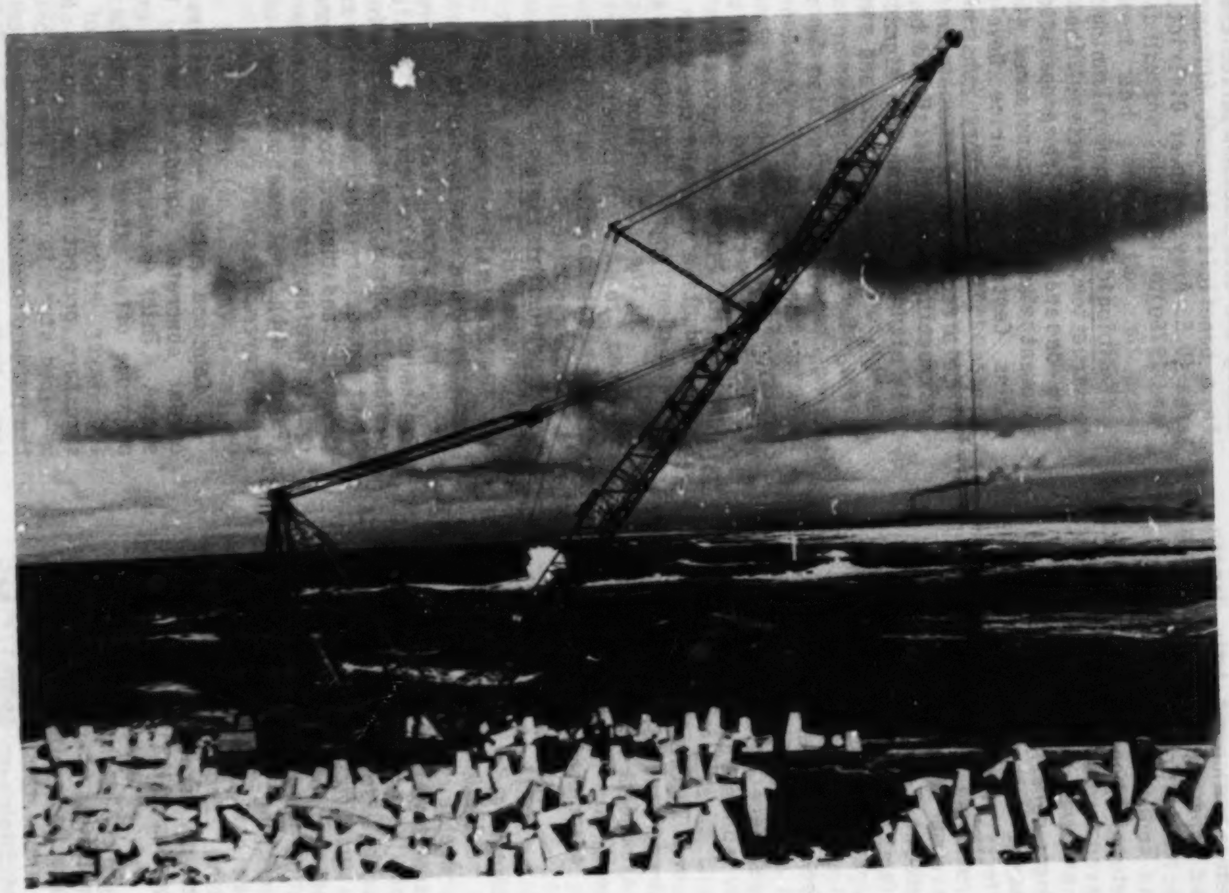


Figure 14. Dolosses are being installed as protective facing on this rubble mound jetty in Humboldt Bay, California. Note north jetty in background. Photograph courtesy of U.S. Army Corps of Engineers, South Pacific Division.

sloped sides and protect the base of the structure from scour and undermining (U.S. Army Corps of Engineers 1973b).

Sheet piles are not satisfactory in high wave energy environments, but can be used where the wave climate is less severe. Steel, used as sheet piles, should be coated to prevent corrosion. Timber must be treated with preservatives to prevent attack by marine invertebrates, such as borers and gribbles. Concrete is immune to pests, but an improper mix can deteriorate rapidly in seawater (U.S. Army Corps of Engineers 1973b).

Expected Life Span

Rubble mound jetties can last up to 50 yr if properly designed and maintained (U.S. Army Engineer District, Portland 1975b). Maintenance includes both replacing displaced armor components after particularly severe storms and major repairs every 15 to 20 yr to replace broken, worn, or lost components. Sheet pile jetties, whether steel, timber or concrete have shorter lifespans due to abrasion by sand and water-borne debris, corrosion by salt water, and attack by borers or gribbles (U.S. Army Corps of Engineers 1973b). They can last anywhere from 10 to 35 yr depending on the conditions of their environment.

Summary of Physical and Biological Impacts

Construction effects. As with any major construction activity in the coastal zone, placement of jetties causes some temporary disturbance, such as turbidity caused by resuspension of bottom sediments. Toxic substances present in sediments can be released (Carstea et al. 1975a). Noise, and air and water pollution will accompany construction activities (U.S. Army Engineer District, St. Paul 1976a). During construction, nearshore currents can be disrupted. Erosion and accretion can occur locally in patterns quite different from those previously existing or those which develop after completion (Anderson 1975). Suspended sediments may reduce primary productivity and smother benthic organisms (Cronin et al. 1971). The area covered by the jetty will be lost as a bottom habitat (Virginia Institute of Marine Science 1976), but a new type of habitat will be created.

Chronic effects. The presence of jetties at a river or bay mouth alters both river outflow and tidal currents (U.S. Army Engineer District, Portland 1975b). These alterations are often felt well into the estuary and may have widespread effects. Altered rates of nutrient and sediment accumulation can occur in salt marshes. Salinity and temperature changes can occur. The tidal prism can be altered since overall circulation patterns within an estuary are affected by the change in water flow through a stabilized channel. The flushing characteristics of the estuary can be changed and wave height often increased in its lower regions (Carstea et al. 1975a).

Outside the estuary, the most significant effect of jetties is the alteration of littoral transport. Littoral transport is obstructed by the jetties; sand is impounded updrift and eroded downdrift. If a single jetty is installed, the opposite side of the inlet can erode severely. Also, a shoal can form at the tip of a single jetty updrift of an inlet and eventually fill in the inlet. The influence of a jetty extends well beyond its immediate vicinity. Downdrift beaches retreat due to sand starvation unless measures are taken to bypass the sand that accumulates updrift of the jetties (Ketchum 1972). Changes in foredune height have been reported downdrift of jetties (Demory 1977).

The channel formed by jetties often migrates from the original location to an area adjacent to one of the jetties, scouring the bottom and causing turbidity. As the channel nears the jetty, the scouring action can erode the base of the jetty and necessitate repairs or strengthening of the structure base. Sandbars tend to migrate seaward in the presence of jetties (Kieslich and Mason 1975). Dredging is usually required to maintain a channel of sufficient depth since the tidal currents are inadequate to keep the channel scoured (U.S. Army Corps of Engineers 1973b).

The placement of jetties destroys

some bottom habitats and creates new ones. Rubble mound structures provide attachment sites for sessile organisms, and the irregular surface can support a diverse community of rocky shore plants and animals (Ortolano and Hill 1972). Sand accretion areas can provide new habitats for shellfish and shorebirds (Snow 1977). Areas where erosion takes place often become populated by fish which require deeper water. Jetty related fisheries can develop (Ortolano and Hill 1972). However, the presence of jetties may limit or alter the normal movement of fish and crustaceans into and out of estuaries (Cronin et al. 1971). Physical changes in water circulation, flushing, current patterns, and shoaling within the estuary may severely degrade or alter existing habitats (U.S. Army Engineer District, Portland 1975b). In some cases altered circulation patterns are beneficial.

Cumulative effects. Most of the effects due to jetties are noticeable in the immediate vicinity and in the embayment or river and coastal area where they are constructed. There is generally little reason to construct several pairs of jetties in proximity. Therefore, cumulative effects due to proliferation of jetties are not obvious. It is possible, however, that numerous jetties along a coastline could have the same cumulative effects upon littoral transport as a numer of groins could.

Structural and Nonstructural Alternatives

Jetties are normally used to provide channel or inlet stabilization and to reduce the amount of dredging required to maintain the inlet or channel. There are different materials and configurations available for jetty construction. It is also possible to use other structures, such as groins, in conjunction with jetties to reduce or modify effects of the jetty on adjacent areas.

Nonstructural alternatives fall into two categories. The first is to do nothing and forego the use of the waterway for navigation and possibly adjacent lands for some form of development. The second alternative is to maintain navigation by means of dredging. This alternative can be very costly and can result in the channel being unusable for certain periods due to the inability of dredging equipment to provide and to maintain desired depths for navigation. It is also possible that the dredging and disposal process will have an impact on the surrounding environment which is far greater than the impact due to jetties.

Regional Considerations

Jetties have been built, or are planned, for virtually every inlet of significant size in the North Pacific (Coastal Region 1). In some cases only a single jetty has been placed but most inlets are stabilized by a pair of jetties. All are placed perpendicular to the shore and are of rubble mound or quarried stone construction. No unique placement constraints apply to this coastal region. Construction materials include rock (usually basalt), quarry stone, and, in at least one case, dolosse. Average life span of jetties in this area is about 50 yr with major repairs expected to be necessary during that period (U.S. Army Engineer District, Portland 1975c, 1976e).

Long-term impacts include erosion and accretion changes, habitat alterations at the jetties and within estuaries, and changes in tidal patterns and water quality. Storm waves have caused severe damage to jetties as a result of scouring (Wong 1970). A number of sand spits have been altered, breached, or destroyed as a result of jetty-caused current changes. The foredune at Tillamook,Oregon, is many times higher than it was before construction of the Tillamook jetty. No summer return of winter sand loss was observed in the first few years following extension of Yaquina Bay, Oregon, jetty (Demory 1977). Jefferson (1974) reported that configuration of some of Oregon's coastal bays has been changed by the construction of jetties. All along the Oregon coast, changes in habitat, apparently connected with presence of or changes in jetties, have been observed (Snow 1977). In one case, a jetty's influence on littoral transport contributed to the breaching of a sand spit. This allowed sand and boulders to enter a protected lagoon and bury most existing commercial oyster beds (Jefferson 1974). Jefferson (1974) also blames jetties for contributing to modification of estuarine salt marsh habitats.

Jetties are commonly found at coastal inlets throughout southern California (Coastal Region 2). In several cases, they are associated with man-made harbors (Reish 1962). Rubble mound construction utilizing rock is most common. No placement constraints are unique to this coastal region. Sea mussels, barnacles, limpets, snails, and other sessile and cryptic organisms populate most of southern California's jetties (Reish 1964). A green algae, Ulva dactylifera, is a pioneer species on newly constructed jetties (Reish 1969) and is soon joined by a variety of marine animals. No unique construction related physical or biological impacts were identified for Coastal Region 2. Long-term impacts were similar to those previously described.

Jetties in the Gulf of Mexico(Coastal Region 3) are placed in inlets in barrier islands, as well as at river mouths. Placement constraints are those previously described. Most are rubble mound structures constructed of stone, including granite. Varying salinity and current regimes often exist on opposite sides of jetties, and if the structure is hooked to protect a harbor, there may often be varying wave climates inside and outside (Gifford 1977). Jetties provide a habitat for sessile and cryptic organisms that attract fish and birds. The physical and biological impacts of jetties have been described previously. In addition to those described, Hastings (1972)reported that fish from more tropical areas were found in the vicinity of jetties. On the channel side of jetties, the organisms tend to be those with a greater tolerance for the rapid salinity changes, periods of low water clarity, and strong tidal currents while those on the outside were tolerant of surf conditions (Hastings 1972). Hastings (1972) further reported that most fish found near jetties were secondary consumers.

Jetties are common in south Florida (Coastal Region 4) and are found at inlets and harbor mouths both on the mainland and on barrier islands. They are used to stabilize inlets, train currents, and protect beaches. Lying perpendicular to the shoreline, they extend beyond the surf zone. Placement constraints are those generally applicable to jetties everywhere. However, the Florida Department of Natural Resources (1973) has pointed out that jetties are not permanently successful in fulfilling their function unless they are integrated with other shore protection measures as part of a comprehensive program covering large stretches of shoreline. No physical or biological impacts unique to this coastal region were found.

No data were found that were unique to jetties in the south, middle, or north Atlantic (Coastal Regions 5, 6, or 7.)

Jetties in the Great Lakes (Coastal Region 8) are often constructed of materials other than rubble mounds. Steel sheet pile cells, cassions, and timber, steel, or concrete cribs are also utilized. Timber and steel sheet piling in single rows are sometimes used in sheltered areas (U.S. Army Corps of Engineers 1973a).

GROINS

Definition

A groin is a rigid structure built out at an angle (usually perpendicular) from the shore to protect it from erosion or to trap sand. A groin may be further defined as permeable or impermeable, depending on whether or not it is designed to pass sand through it.

Groynes (British), spur dikes, and wing dams are included in this definition. Sometimes the word jetty is used interchangeably with groins; however, jetties generally have a different function. Under certain conditions a structure may be carrying out functions normally associated with both jetties and groins. An example would be directing stream flow in a river,while concurrently stabilizing a beach.

Structure Functions

The most common function of a groin

is to provide or maintain a beach. Groins can be designed in various configurations to do any of the following:

- o build or widen a beach by trapping littoral drift;
- o stabilize a beach by reducing the rate of sand loss;
- o prevent accretion in a downdrift area by acting as a littoral barrier.

The above functions all assume existence of either a sandy beach and/or a littoral supply of sand. Groins can affect areas both updrift and downdrift. The functions of building, or stabilizing a beach may have the effect of starving an adjoining area.

Site Characteristics and Environmental Conditions

Groins are constructed on many types of shorelines, but most commonly on shallow, sandy, or shingle beaches. Since they can be used to prevent erosion, build or widen beaches,or prevent downdrift accretion, their siting on the shoreline is dictated by their intended function (Figures 15, 16, and 17). For a groin or groin system to function, there must be a supply of sand provided by littoral transport. Other than this common characteristic, no generalizations can be made concerning environmental conditions or groin sites.

Placement Constraints

Engineering. A groin must be designed for a specific site. There is no best design,optimum choice of construction,nor ideal length or spacing between groins that can be applied generally to all situations. The substrate of the site must be studied to determine structural limitations, material availability, and maintenance requirements (U.S. Army Corps of Engineers 1973b). Other characteristics of a shoreline must also be known before a single groin or a groin field is constructed. These are angle of wave approach, volume of littoral drift, wave strength, current, and shoaling patterns (Horikawa and Sonu 1968).

If the objective of the groin or groin field is to trap sand and to minimize sand movement downcoast, groins should be built to a height that will prevent normal high water from carrying sand over them. When continued movement of sand is desired, the height of groins should be near to or below normal high tide level (Balsillie and Berg 1973). Length of groins is also dependent on the degree of littoral drift obstruction desired and on existing and desired beach slope (U.S. Army Corps of Engineers 1973b). Length is measured from the groin's landward end at the berm to its seaward end. The seaward end usually extends to the point where incoming swells exert the greatest force on the sand bottom (Coen-Cagli 1932).

The spacing of groins in a groin field is subject to a number of factors. As a general rule, groins should be separated by a distance two to four times their length (Savage 1959, U.S. Army Corps of Engineers 1973b). However, spacing must assure that minimum beach width is maintained. A more detailed discussion of the factors involved in groin spacing is found in the Shore Protection Manual (U.S. Army Corps of Engineers 1973b).

Though the majority of groins are straight, some are built with a lengthwise curve or are L-, Z-, or T-shaped (Balsillie and Berg 1973). Their crests can be level or can slope downwards toward the seaward end (U.S. Army Corps of Engineers 1973b). In a groin field, successive downdrift groins can be made progressively shorter or lower, with the latter variation being preferable (Coen-Cagli 1932).

Whatever the design of groins, starvation of downdrift beaches should be prevented. If a newly constructed groin will capture nearly all littoral drift, artificial nourishment is desirable to assure a supply of sand to downcoast beaches (Sanko 1975). Another method of filling behind a groin involves placing a weir or series of weirs along its length. This allows a portion of the littoral drift to continue downdrift (U.S. Army Corps of Engineers 1973b). This structure is effective only if there is no movement of the stone material.

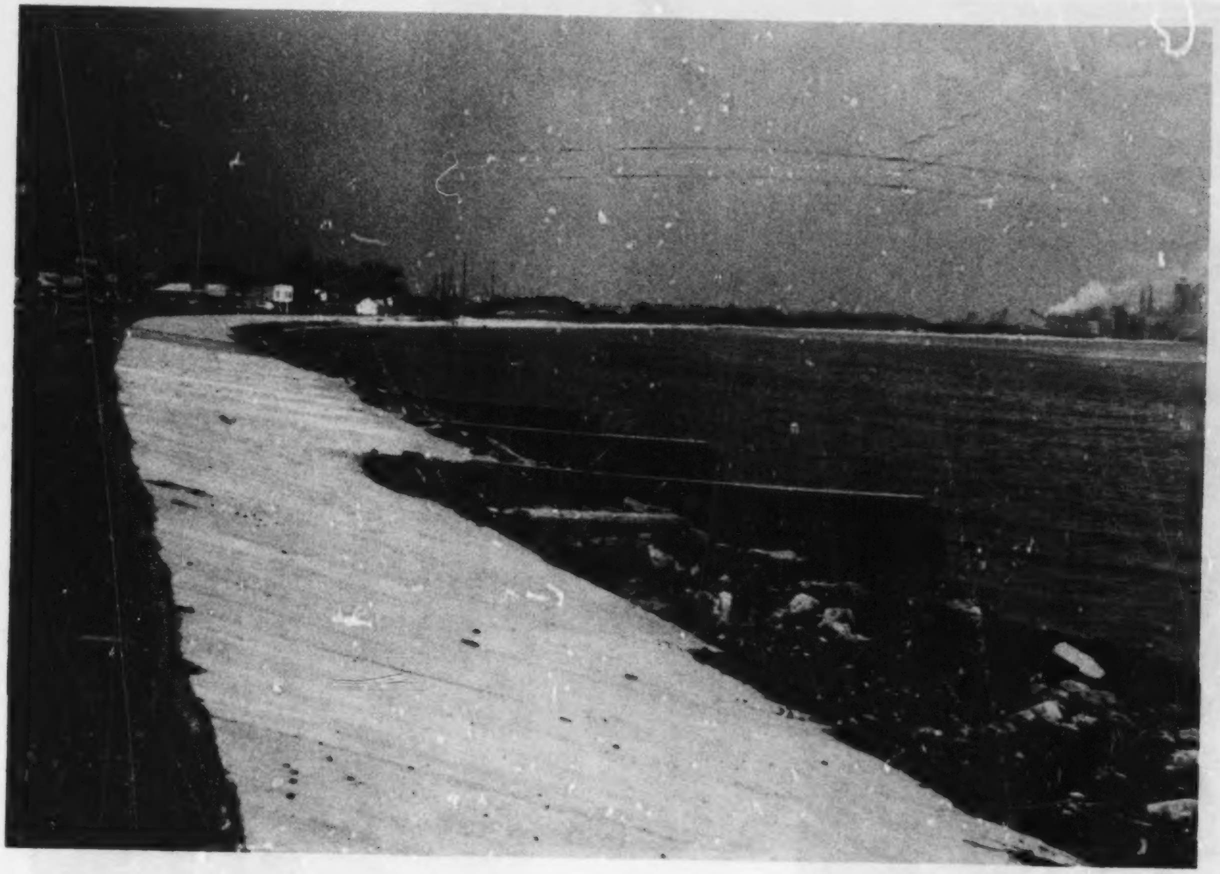


Figure 15. Concrete groins at the base of a revetment on the Gulf coast of Florida. Photograph by E. L. Mulvihill.

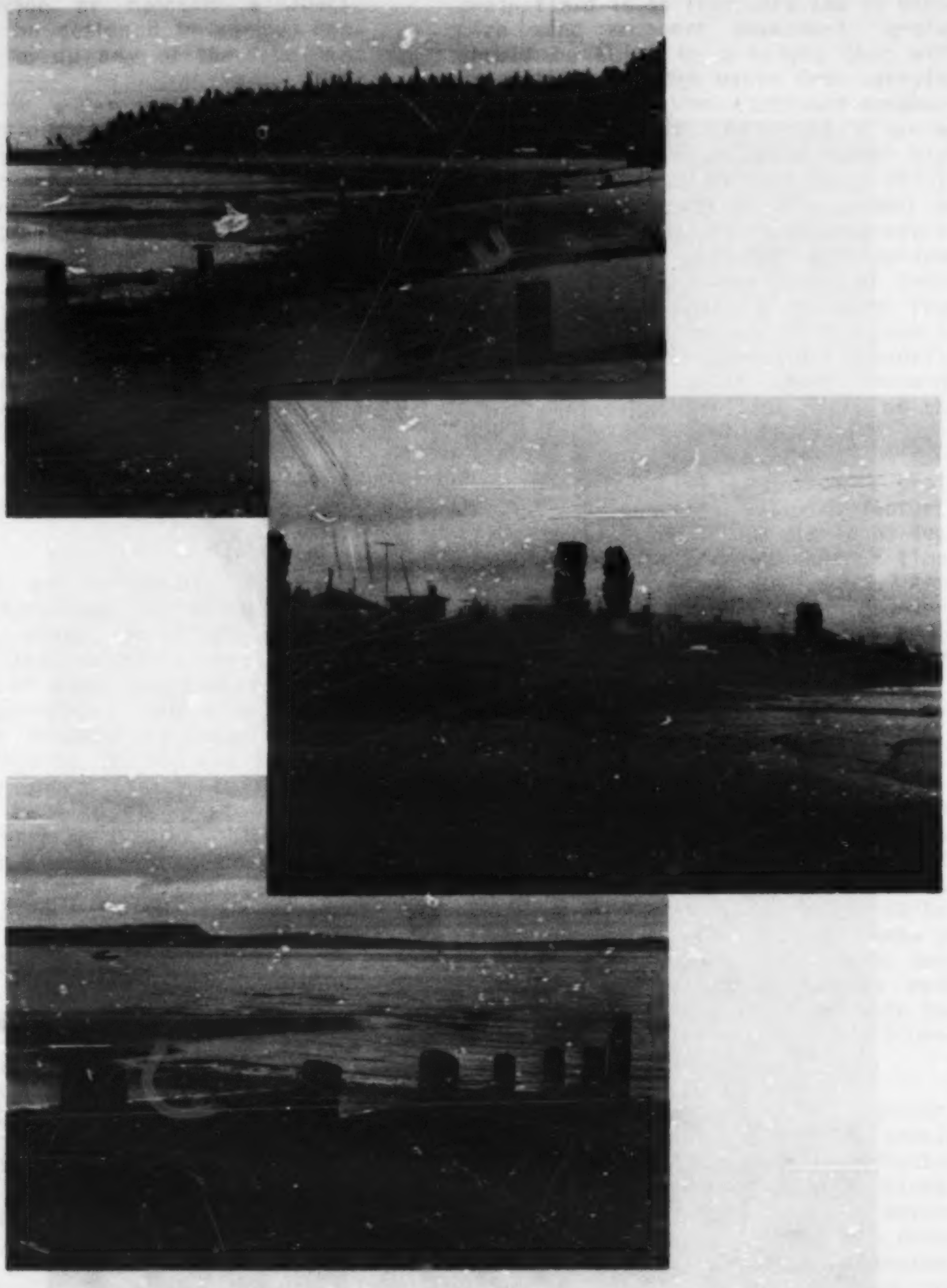


Figure 16. Timber pile groins, Puget Sound, Washington. Photographs by C. A. Francisco.

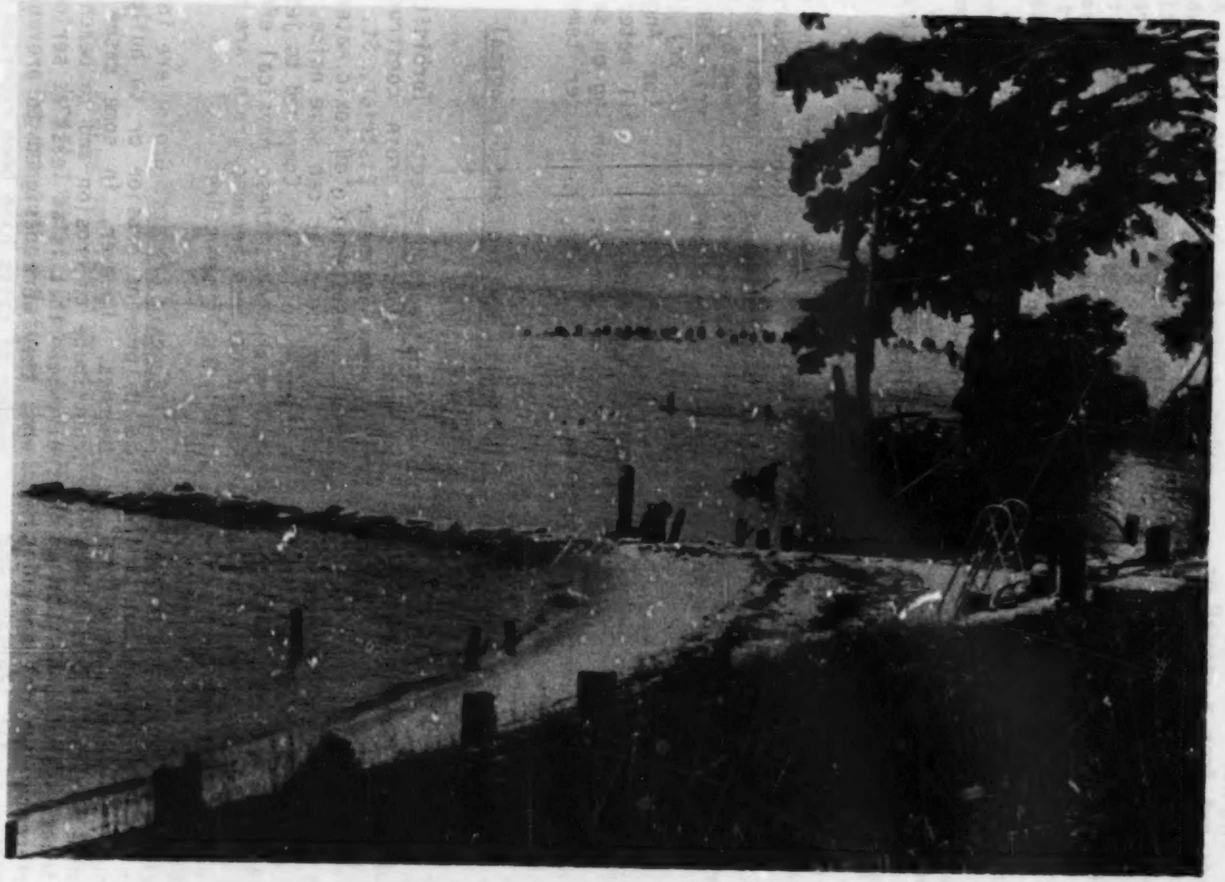


Figure 17. Rubble mound groin in the southeastern United States. Photograph by V. J. Bellis.

It is imperative that groins extend to the crest of the beach berm, or high wave action will cause flanking (U.S. Army Corps of Engineers 1973b). If the groin extends out from a seawall or bulkhead, it should be solidly anchored to that structure (Coen-Cagli 1932).

Socioeconomic. The cost of groins varies greatly, depending on construction materials, anticipated wave action, tidal range, and whether additional beach nourishment will be necessary (U.S. Army Corps of Engineers 1971b). A method of determining economic feasibility of groin construction involves comparison of construction and maintenance costs with the cost of periodic beach nourishment (Berg and Watts 1971). Prefabricated groins are often economical to install. Timber groins and low permeable structures are probably the most economical for an individual property owner (Horikawa and Sonu 1968, Pallet and Dobbie 1969), Gabion groins (Figure 18) require extensive maintenance. They are also unsightly and vulnerable to damage by drifting logs or other heavy debris. The aesthetic effects of groin placement should not be neglected. A sandy beach is more attractive than an eroded one. However, the groins that protect it should be as unobtrusive as possible (Coastal Plains Center for Marine Development Service 1973). Construction activities should not interfere with recreational use of a beach.

Biological. Very little information is available concerning biological constraints on placement of groins. Carstea et al. (1975a) recommended that restrictions be placed on the amount of sediment resuspended by construction activities. The effects of groin construction and siting on wildlife propagation and movement should be known and efforts made to minimize adverse effects (Snow 1973). Construction should be planned to avoid interference with fish spawning areas or migratory routes (Persaud and Wilkins 1976). Groins which capture all littoral drift, thus encouraging or aggravating downbeach erosion, should not be constructed. Such erosion can degrade aquatic resources.

Construction Materials

Groins can be built of almost any material which will remain in place and not deteriorate rapidly. Impermeable groins are often constructed of sheet piles supported by piles (U.S. Army Corps of Engineers 1973b). The sheet piles are wood, steel, or a combination. Other materials for impermeable groins include quarried stone, concrete, rubble, and asphalt (Figure 19). Permeable groins (Figure 20) are constructed of similar materials, as well as of sandbags, sand-filled nylon tubes, wood, and earth (Erchinger 1970). Stone groins should have filter cloth under them to prolong the life of the structure by delaying settling into the substrate.

Expected Life Span

Recorded life spans of groins vary from 2 to 50 yr. Rubble or quarried stone is reported as the longest lasting construction material, followed by steel (25 yr), treated wood (20 yr), aluminum (15 yr), and nylon bags (2 yr) (U.S. Army Engineer District, Los Angeles 1974a, Chabreck 1968). All materials vary in permanence, depending on salinity, wave climate, and water temperature.

Summary of Physical and Biological Impacts

Construction effects. Turbidity is a major impact of groin construction (U.S. Army Engineer District, St. Paul 1976b). Resuspension of toxic materials can also occur, as can some noise, air, and water pollution. Compared to jetties and breakwaters, these physical effects should be less because groins are relatively small structures.

Chronic effects. Groins are intended to prevent erosion or to build the beaches. However, in some cases they contribute to erosion and to beach loss elsewhere that is at least as serious as what they were designed to prevent. A number of cases have been reported where downdrift beach erosion was aggravated. An example of this is described by Pallet and Dobbie (1969) where downdrift cliff erosion was increased by the presence of a groin system. In spite of this problem, groins serve their intended functions. Beaches are stabilized,

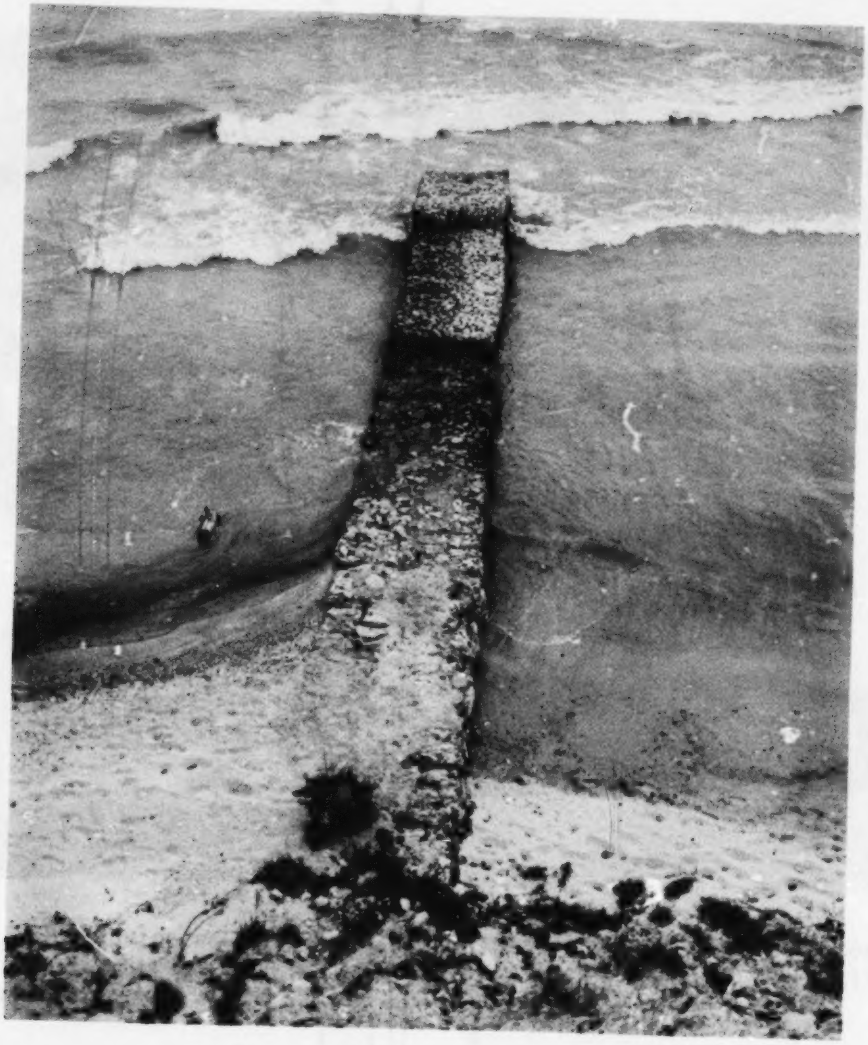


Figure 18. Gabions are used to construct groins on the Great Lakes. Photograph courtesy of State of Michigan, Department of Natural Resources.

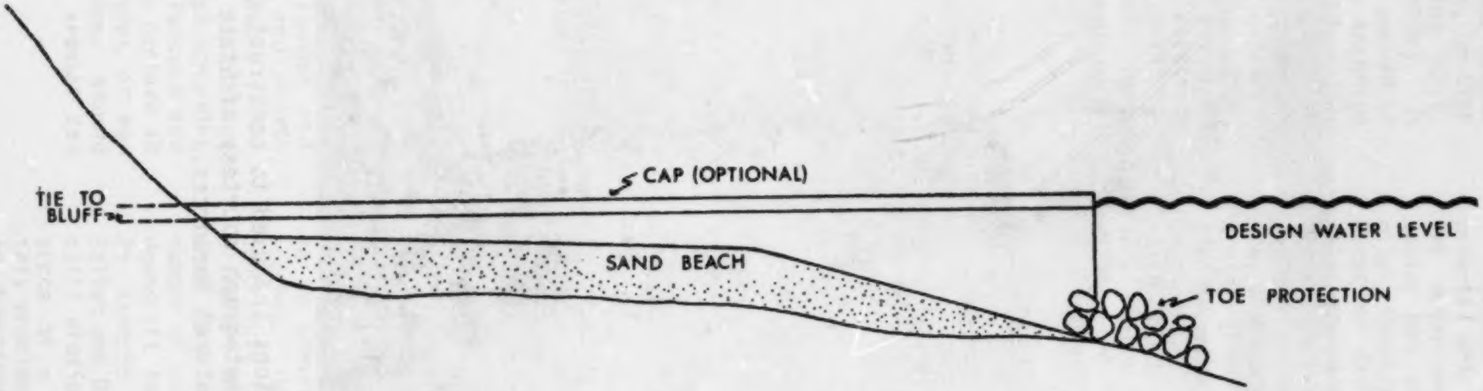

CAP (OPTIONAL)
TIE TO BLUFF
DESIGN WATER LEVEL
SAND BEACH
TOE PROTECTION

Figure 19. Side view of an impermeable groin. Construction materials, dimensions and details to be determined by particular site conditions.

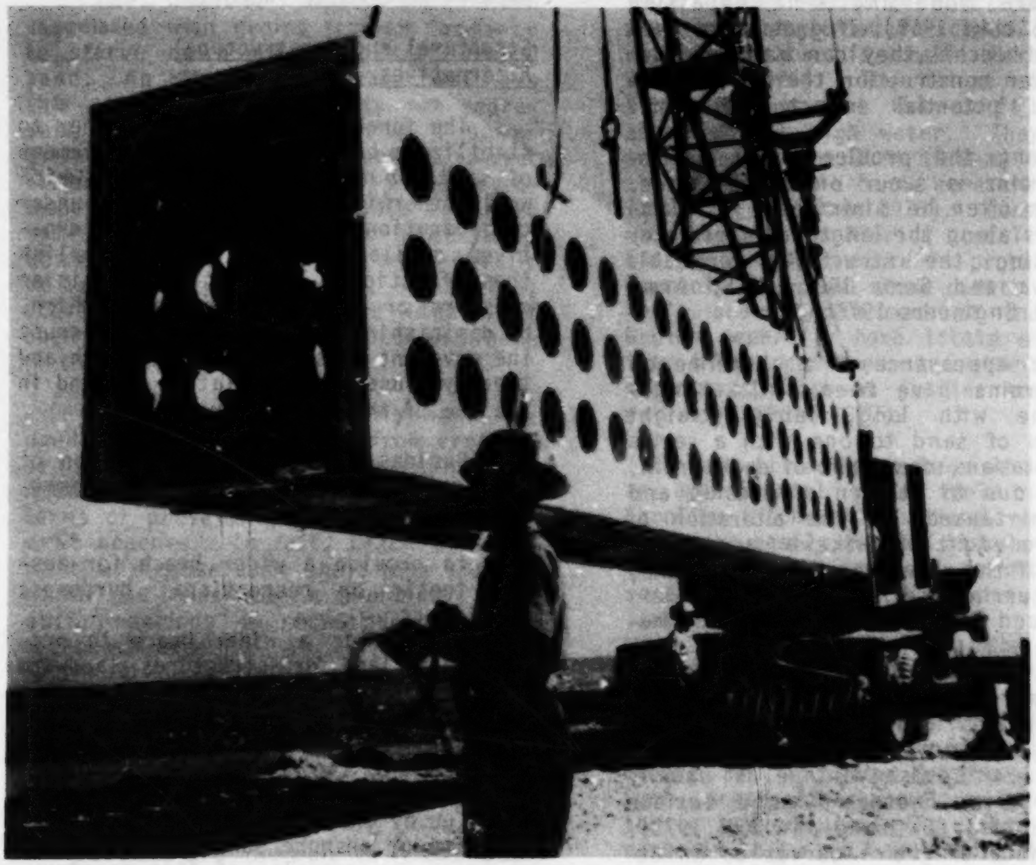


Figure 20. Prefabricated permeable groin. This component has also been used in the construction of breakwaters. Photograph courtesy of Portland Cement Association.

fore dunes are protected, and beach width can be increased by careful placement of groins (Berg and Watts 1971, Pallet and Dobbie 1969). Downdrift beach starvation results when groins completely obstruct littoral drift. Downdrift beaches will recede until the groins are filled and sand bypassing occurs (Schijf 1959). If groins are used to widen beaches,they can be filled with sand after construction thereby lessening the potential impact downdrift.

Among the problems that accompany groins is scour on the lee side. This can often be minimized by including weirs along the length of a groin or by making the structure permeable (Horikawa and Sonu 1968; U.S. Army Corps of Engineers 1973b).

The appearance of a shoreline on which groins have been built changes from one with long, fairly straight stretches of sand to one with a series of indentations downdrift of each groin. This is due to pattern of erosion and accretion caused by the alteration of longshore drift (Horikawa and Sonu 1968). If the structures are permeable, this recurring series of arcs is less pronounced than if they are impermeable.

The accretion of sand behind groins buries those bottom organisms which cannot move away from the area. However, this disadvantage is usually offset by the increased sand surface area provided (Ortolano and Hill 1972). The surface of groins serves as an attachment site for sessile organisms (Cronin et al. 1969), and groins often provide a protected area for establishment of beach vegetation (Garbisch et al. 1975). Groins also attract fishes and often provide excellent fishing spots. Before a stable shoreline is achieved, scouring and filling around groins affects productivity by keeping the water turbid and by providing a poor habitat for marine plants and animals (Cronin et al. 1969, Garbisch et al. 1975).

Cumulative effects. Cumulative effects of numerous groins in an area are similar to the summation of effects caused by single groins.They are, however, more widespread. Because groins tend to accelerate downdrift beach erosion by reducing the amount of sand transported to them, the placement of one groin often leads to the need for another a distance away. A series of groins will take longer to fill, prolonging the period in which downdrift shorelines are exposed to erosive factors.

Structural and Nonstructural Alternatives

The function of groins is either to stabilize a beach by preventing movement of sand, or to trap littoral sand which would otherwise move past the area under consideration. There are few alternatives available which will accomplish these functions. The most obvious is an offshore or parallel breakwater which, by diminishing wave energy, will disrupt the movement of sand along the beach and thereby cause an accumulation of sand in the lee of the breakwater.

Besides the immediate function of the groin, two other purposes are immediately apparent:

- o to provide a wider beach for aesthetic or recreational purposes;
- o to provide a wider beach to protect land or structures landward of the beach.

Both of these objectives can be accomplished by the nonstructural alternative of beach nourishment. The beach is built up by artifically adding sand from offshore or onshore sand sources. There are numerous examples of this construction practice, particularly along the east coast of the United States. This process is generally a continuous one since the forces that eroded the beach initially are probably still at work and will erode it after nourishment. Thus, further nourishment is required at a later date.

If the purpose of the wider beach is for protection, there are several structural alternatives available. A breakwater will tend to widen the beach in its lee. It will also assist in dissipating energy from wave attack, thus providing protection to structures or land in its lee. If the purpose of the wider beach is simply shore protection, and the wider beach serves no other functional purpose, then the upland area can be protected by means of revetments, bulkheads, or seawalls as alternatives to groins.

The negative impact most often associated with groins is their tendency to starve downdrift beaches of littoral sand. An offshore breakwater will have this same effect so it does not represent an attractive alternative if downdrift starvation is to be avoided. Direct armoring of the shoreline by the revetments, bulkheads, or seawalls can have some effect on shorelines immediately downdrift; but the impact will normally be less than that of groins. Of course, these structures will have impacts of their own which are described elsewhere in the report.

Artificial beach nourishment by dredging or truck hauling from areas of sand surplus probably represents the most attractive alternative to groins in terms of preventing starvation of downdrift beaches. In fact, beach nourishment may cause some short term impacts which can constitute a problem if done during periods of recreational uses of the beach area.

Regional Considerations

No information was found that was unique to groins in the north Pacific (Coastal Region 1).

Groins are common in those portions of southern California (Coastal Region 2) where beaches exist. Though permeable groins with removable panels are sometimes used (Riese 1971), beach nourishment is usually required(Carlisle 1977). Southern California had a large volume of littoral drift (Berg and Watts 1971), but it has decreased in recent years due to reduced volumes of sand reaching the sea from the uplands and from loss of sand into offshore submarine canyons (Carlisle 1977). They also provide a habitat for rocky shore organisms (U.S. Army Engineer District, Los Angeles 1974d).

Groins are frequently used as alternatives to seawalls and bulkheads for shore protection in the Gulf of Mexico, south Florida, and the south Atlantic (Coastal Regions 3, 4 and 5). They are rarely completely successful unless they are planned as part of an area-wide comprehensive shore protection program (Florida Department of Natural Resources 1973). They should be constructed only where the angle of incidence of waves with the shore is small (Herbich and Schiller 1976). The height should be kept low, no more than 1 ft (0.3 m) above normal high water. They should terminate at the 3 ft (0.9 m) depth and the length should be no more than 100 ft (30.5 m) (Collier 1975). Construction materials on the Florida coastline vary, but preformed concrete is probably more commonly used than stone due to the latter's scarcity in much of the State. Groins generally have little effect on the biota compared to other larger structures, such as jetties and breakwaters (Gifford 1977).

Sand-filled nylon bags were used in an experimental groin field in North Carolina (Machemehl and Bumgarner 1974). They were easily damaged and shortlived, but inexpensive compared to other construction materials. They were also relatively easy to place.

Groins are common in the middle Atlantic (Coastal Region 6). One study reported 45 such structures in only 8,400 ft (2,560 m) of shoreline in Chesapeake Bay (Schultz and Ashby 1967). Rock construction worked most satisfactorily and required the least maintenance in this area. Well-ring construction was tried, but proved unsatisfactory since some of the rings washed away and maintenance requirements were high (Schultz and Ashby 1967). Circulation patterns in Chesapeake Bay areas were altered by groin placement. This affected erosion patterns, as well as nutrient and sediment accumulation rates in marshes (Carstea et al. 1975a). When benthic invertebrate loss and gain due to construction of groins were compared, it was estimated that the net effect was neither beneficial nor detrimental (U.S. Army Engineer District,New York 1976). The same document reports that fish will be attracted to groin areas.

Groins are common shore protection

structures in the north Atlantic (Coastal Region 7), particularly along the New Jersey and Long Island coastlines. No information unique to groins in this coastal region was found.

Groins are used throughout the Great Lakes (Coastal Region 8) to protect both shallow and steep, eroding shorelines. The Michigan Demonstration Erosion Control Program involves an ongoing study of the effectiveness of a number of shore protection devices, including groins (Brater et al.1974, 1975, Marks and Clinton 1974). Several different designs and materials are being investigated. Some of the designs have proved successful at retarding erosion while others have failed. A great deal has been learned concerning erosion on Great Lakes shorelines. Filters are necessary to prevent undermining or settling on clay and sand substrates (Marks and Clinton 1974). Impermeable groins are preferable for use in the Great Lakes (Lee 1961). Basic design criteria generally differ little from that of the groins in the ocean. One difference is that Brater (1954) recommends that they terminate short of the 6 ft (1.8 m) depth contour for maximum effectiveness.

BULKHEADS

Definition

A bulkhead is a structure or partition built to prevent sliding of the land behind it. It is normally vertical, but may consist of a series of vertical sections stepped back from the water and built parallel or nearly parallel to the shoreline. There is no precise distinction between bulkheads and seawalls, although some authors suggest the primary purpose of a bulkhead is to prevent sliding of the land while the primary purpose of a seawall is to protect the upland area from wave attack (U.S. Army Corps of Engineers 1973b). Thus, a seawall might project above the elevation of the upland area, while a bulkhead would terminate at or below that elevation.

Since bulkheads, seawalls, and revetments are all generally parallel to the shoreline and separate land from water areas, there is some confusion of identification and the same structure may have different names in different areas.

Structure Functions

Bulkheads are built to prevent sliding of the land behind the structure. In this capacity they serve a number of diverse functions, such as protection of uplands from erosion, creation of shorefront real estate, moorage of vessels, and other aesthetic or recreational uses. However, the utility of bulkheads is that they allow protection against waves and currents without loss of land. Thus, one major function of the structure is to delineate between land and water with no loss of land area. In many areas bulkheads are built along shorelines and then backfilled to create or reclaim waterfront land. Bulkheads are often used where land is particularly valuable or where there is insufficient land available to provide a sloped surface or beach for protection.

Bulkheads provide a vertical separation of land and water which allows mooring of vessels adjacent to land without the necessity of a pier. A bulkhead, either alone or in conjunction with a wharf, is often used for cargo handling facilities in ports.

Site Characteristics and Environmental Conditions

Bulkheads are built parallel to and on the shoreline. The location of a bulkhead on the shoreline is generally in the vicinity of the mean high waterline, but placement can range from above mean high water to below mean low water depending upon the structure's function. For example, when bulkheads are built for boat mooring, the structure generally is placed below the mean high waterline and the bottom, in front of the structure, is dredged to allow access at low tides. Bulkheads thus are found in all tidal zones ranging from subtidal to terrestrial. They are generally installed in areas of relatively low wave energy because waves will usually cause scour and subsequent structural degradation.

Bulkheads and seawalls, generally built to separate land from water areas, can serve a number of diverse functions (see Structure Functions section). They are found in many types of coastal habitats including areas with eroding shorelines, narrow fringe marshes, salt and freshwater marshes, and other areas with eroding mud, silt, sand, or shingle beaches. Because bulkheads and seawalls are expensive to build, they typically are found in the developed areas where shorefront real estate is valuable.

Placement Constraints

Engineering. A number of factors must be considered in bulkhead design and construction. Important considerations include height and location on beach, toe protection, shape of the structure, pile penetration, structural anchorage, alignment with adjacent bulkheads, and erosion of supporting beach materials from behind the structure.

Many authors recommend that bulkheads be constructed above the mean high waterline for both engineering and biological reasons (see Biological Constraints section). Bulkhead height and placement on the shoreline should be such that waves do not overtop the structure and erode away supporting beach material, or saturate the soil and cause structural failure due to the buildup of hydrostatic pressures. When bulkheads are located on the shoreline so that they are regularly exposed to wave action,the equilibrium of the shore profile is disrupted. The foreshore typically steepens and higher waves reach the structure causing increased toe scour and structural damage from undermining (Earattupuzha and Raman 1972).

Toe protection can help prevent scour at the toe of a bulkhead and also protect the structure against changing beach profiles. Wave energy is deflected as waves break against bulkheads (Figure 21). Wave energy which is not dissipated by the structure can cause scouring of material at the toe of the bulkhead. Important factors in determining toe scour include wave height and steepness, beach slope, roughness and slope of the bulkhead, and beach sand size (Chestnutt and Schiller 1971, McCartney 1976). In general, structures which are not vertical and have rougher faces, such as revetments or stepped concrete seawalls, tend to reflect less wave energy seaward and are less affected by toe scour (Coen-Cagli 1932, Pallet and Dobbie 1969, Sanko 1975).

Adequate pile penetration is another means of preventing undermining of bulkheads from toe scour. It also prevents the toe of the structure from sliding seaward (Collier 1975). Sheet piling must be driven to a depth to withstand the outward pressure from materials behind the structure (Ayers and Stokes 1976). Generally pilings are driven to a depth such that at least two-thirds of the piles are below ground (Michigan Sea Grant Advisory Program undated).

Bulkheads should be securely anchored at their ends and along their length. Adequate tiebacks along the length of the structure prevent seaward tilting (Collier 1975) (Figure 22). Tieback rods should be coated or wrapped to prevent corrosion. Both ends of a bulkhead should be secured to prevent structural failure due to erosion of materials from behind the bulkhead and from the shore adjoining the structure. Wing or cut-off walls are two methods of preventing such erosion and of tying the structure to the shore (Collier 1975, Michigan Sea Grant Advisory Program undated). In areas where bulkheads are adjacent to each other additional anchorage comes from alignment of the structures. Irregular alignment of bulkheads can cause "side erosion and cavitation by reflected corner waves" (Bauer 1975).

Supporting materials behind bulkheads may be washed away by leaching of sand through cracks, weep holes, and joints in the structure. Addition of a filter cloth to the structure's design will prevent such erosion and allow water drainage(Barrett 1966, Collier 1975, Dunham and Barrett 1974). In areas where the soil has a high silt or clay content, the addition of a 6-inch (15-cm) sand pad between the filter cloth and

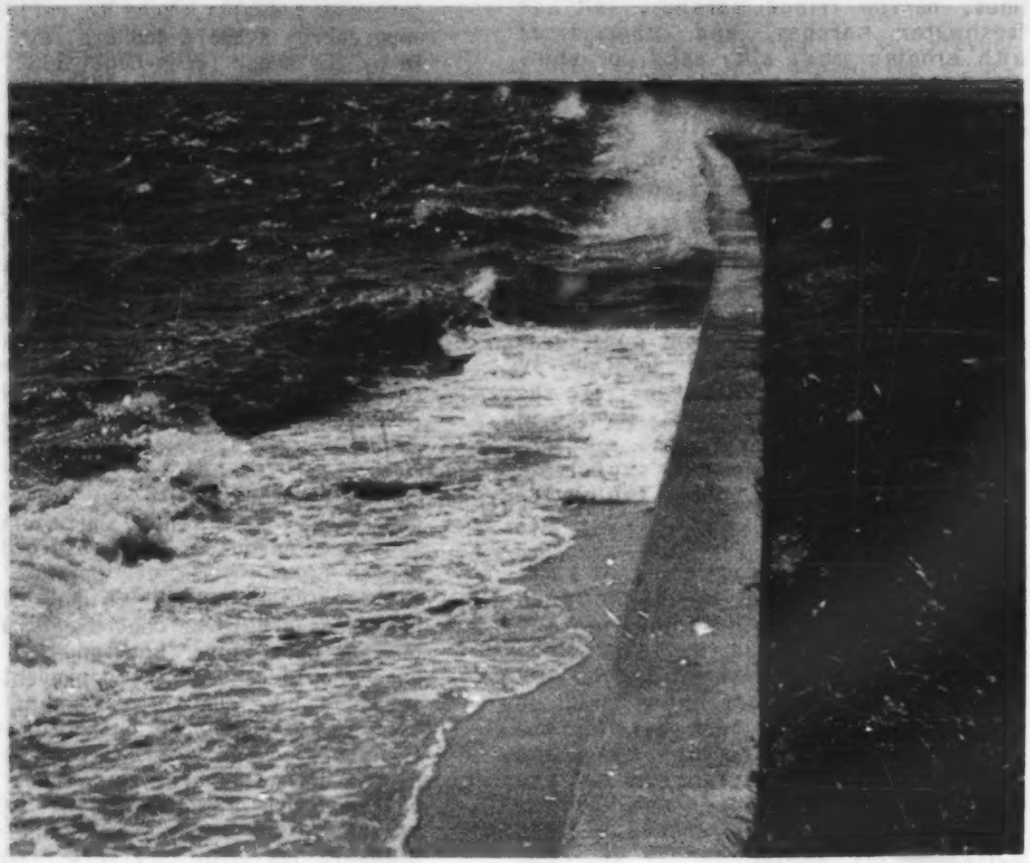


Figure 21. Waves breaking against the concrete bulkhead bordering the causeway in Apalachicola Bay, Florida. Photograph by E. L. Mulvihill.

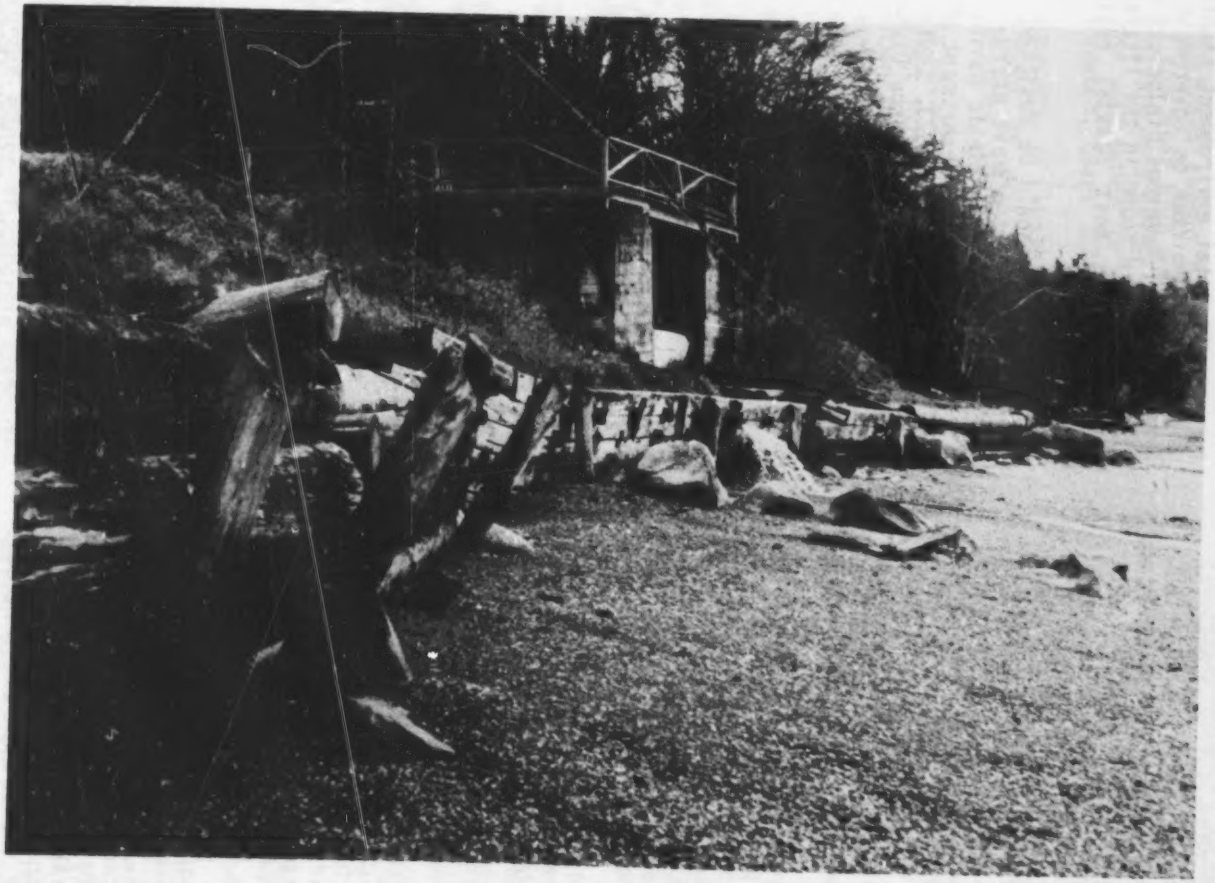


Figure 22. Wooden sheet pile bulkhead at low tide. The pressure of the embankment caused the top of the structure to tilt seaward. This probably resulted from inadequate anchorage and undermining of the structure at its toe. Photograph by T. Terich.

the soil embankment will help prevent loss of silt and clogging of the filter (Dunham and Barrett 1974).

Socioeconomic. Bulkheads can severely limit recreational activities on shorelines (Brater 1954). Several authors urge consideration of the effect a bulkhead will have on access to public beaches prior to construction (Coastal Plains Center for Marine Development Service 1973, McAllister 1977, Snow 1973). Bulkheads can affect swimming, water skiing, diving, fishing, and shellfishing (Carstea et al.1975a; Center for the Environment and Man, Inc. 1971). Borrow areas,which are sometimes created to provide backfill material,may pose a hazard to unsuspecting waders, swimmers, and fishermen.

The appearance of a bulkhead,both alone and as part of the overall shoreline, is an important consideration.Snow (1973) advocates designing bulkheads to blend in with the surrounding shoreline. The South Carolina Marine Resources Division (1974) encourages applications for bulkheads that will aesthetically and/or ecologically enhance the marine environment in areas that have been extensively developed. This agency also discourages bulkheads which have sharp angle turns because trash may accumulate there.

Construction and maintenance costs are an important determinant of the type of structure built at a given location. Bulkheads and seawalls are generally very expensive to construct and maintain. Initial construction and maintenance costs for the design life of the project vary, depending upon site conditions, geographic region, materials used, and massiveness and design of the structure. Initial construction costs can range from $30.00 to over $500.00 per linear foot of protection for more massive seawalls. Local availability of the suitable construction materials influences cost of the structures. The cost of maintenance depends upon labor expenses, material costs, and frequency of repair. In general, poured concrete structures are the most expensive to build,with stepped designs more expensive than either the vertical or sloped structures (Bellis et al. 1975, Sanko 1975).

Biological. When planning bulkhead construction, the effects of the structure on the total environment should be considered (Committee on Government Operations 1970). Numerous biological considerations were found in the literature which apply to most coastal regions:

- Bulkheads should be designed so that reflected wave energy does not destroy stable marine bottoms (Florida Department of Natural Resources 1973, South Caroline Marine Resource Division 1974).
- Bulkhead construction should avoid sharp angle turns be cause this may create flushing or shoaling problems (Bauer 1975, South Carolina Marine Resources Division 1974).
- Bulkheads should be designed to minimize damage to fish and shellfish habitats (Snow 1973).
- Vertically designed bulkheads, especially when they protrude out to minus tide levels in bays and estuaries, eliminate protective habitat for salmon fry (Stockley 1974). Stair-step design bulkheads or riprap revetments on a 45 or less degree angle provide protective habitat for salmon fry (Heiser and Finn 1970).
- Toes of bulkheads should not intrude into fish spawning beaches (Millikan et al. 1974).
- Fill material should not be excavated from shallow water and productive wetlands (Carstea et al. 1976).
- When possible, existing shoreline vegetation should remain undisturbed and/or enhanced for use in shoreline stabilization (Florida Game and Freshwater Fish Commission 1975).

- Marsh and mangrove edges should not be bulkheaded because this eliminates productive fish and wildlife habitat (Carstea et al. 1976, Silberhorn et al. 1974).
- Bulkheads should be set landward of the mean high waterline because this allows a buffer strip of shoreline vegetation to remain (Carroll undated, Clark 1974).
- Amounts of suspended sediments should be restricted during construction (Carstea et al. 1975a).
- Bulkheads which would adversely affect littoral drift and sand deposition on barrier and sand islands and sand beaches are not acceptable (U.S. Department of the Interior, Fish and Wildlife Service 1975b).

Vertical wooden, steel, and concrete bulkheads provide poor habitats for marine organisms (Gantt 1975). The other biological considerations may be found in the Summary of Physical and Biological Impacts section.

Construction Materials

There are two structural classes of bulkheads. Massive freestanding gravity structures, sometimes called seawalls, make up the first class (Figure 23). Seawalls have two functional components, the stem and the base. The stem of the structure may be curved, vertical, or inclined and is designed to withstand the full force of oncoming waves. The stem generally is constructed of rubble or concrete. The base often includes foundation piles which support the structure and prevent settling, and sheet pile cut-off walls which help to prevent loss of foundation material (Collier 1975, U.S. Army Corps of Engineers 1973b).

The second class of bulkheads is constructed either of concrete slabs or sheet piles that are driven into the ground and anchored by tie rods. Construction materials include steel, concrete, timber, or combinations of these materials. Pipes, cables, tires, wire netting, and baled hay have also been used as construction materials in temporary bulkhead structures to promote the establishment of shoreline vegetation (Webb and Dodd 1976). Other materials such as plywood, sheet metal, and fiberglass panels have limited usefulness (Bellis et al. 1975).

Steel sheet piling is a commonly used bulkhead construction material in the Great Lakes. About 70% of all bulkhead projects in the Chicago Corps of Engineers District use steel sheet piling (Boberschmidt et al. 1976). Steel sheet piling, when used to construct bulkheads, should be interlocked, driven into the ground, and tied back for stability. Steel corrodes in warm moist marine climates and should be protected with plastic, bitumin, concrete, or other suitable materials or should be made of a chemical composition resistant to marine environments (Collier 1975). Cellular steel sheet pile bulkheads are often used in place of sheet pile bulkheads when the ground substrate cannot be penetrated due to rocks near the surface (U.S. Army Corps of Engineers 1973b).

Concrete bulkheads are commonly used in Florida and other more tropical climates due to their durability in comparison to steel or timber structures (Gantt 1975). Concrete bulkheads may be vertical, sloped, concave, convex, or stair-stepped. They are, generally, either cast in place or constructed of concrete slabs with a cast-in-place concrete cap (Figure 24).

Wood is the most popular type of construction material (Figures 25 and 26). The timber should be treated with a wood preservative in warmer areas where decay and rot, insects, or marine borers pose a problem (Collier 1975). The components of timber sheet pile bulkheads usually include piles, walers, sheet piles, tie rods, and deadmen or anchor piles (Figure 27). Piles are driven or jetted into the beach, and walers are bolted horizontally to the landward side of the piles. Tie rods are also secured to the piles and attached to anchor piles or deadmen behind the structure. Timber sheet piling is bolted or nailed to the walers. Piles and walers are generally made of heavy

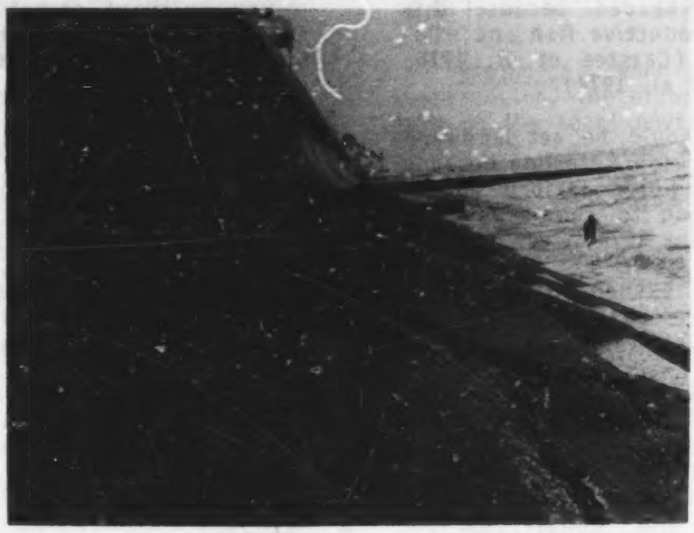


Figure 23. Concrete seawall in Florida. Note signs of wave damage to the base of the structure. Photograph courtesy of Florida Department of Natural Resources.

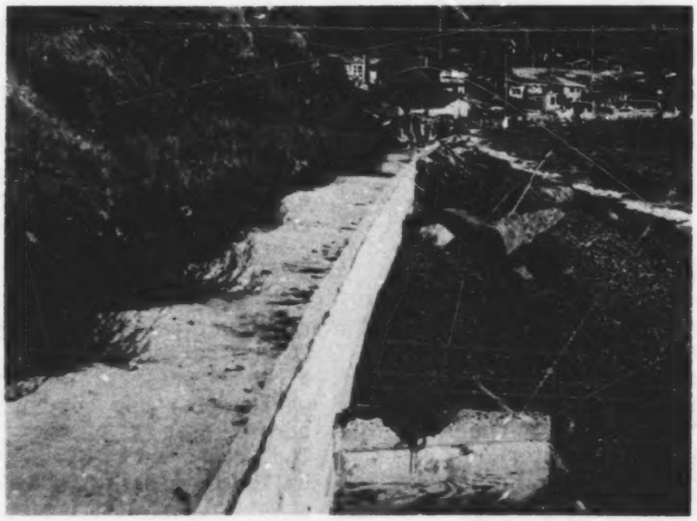


Figure 24. Concrete bulkhead on Fidalgo Island, Washington. Photograph by T. Terich.

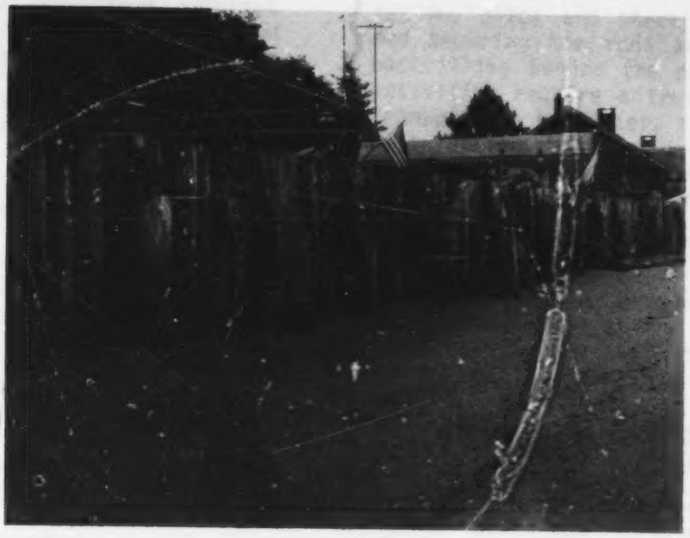


Figure 25. Bulkhead constructed of a series of wood piles. Photograph by C. A. Francisco.

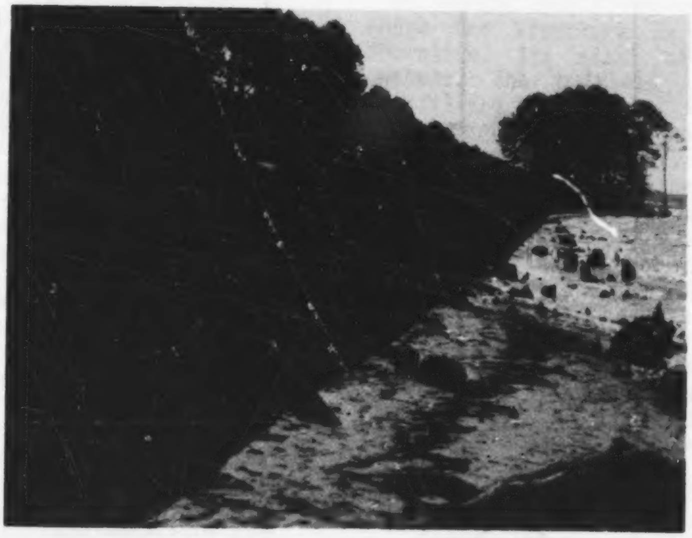


Figure 26. Wooden sheet pile bulkhead along the Gulf coast of Florida. Photograph by E. L. Mulvihill.

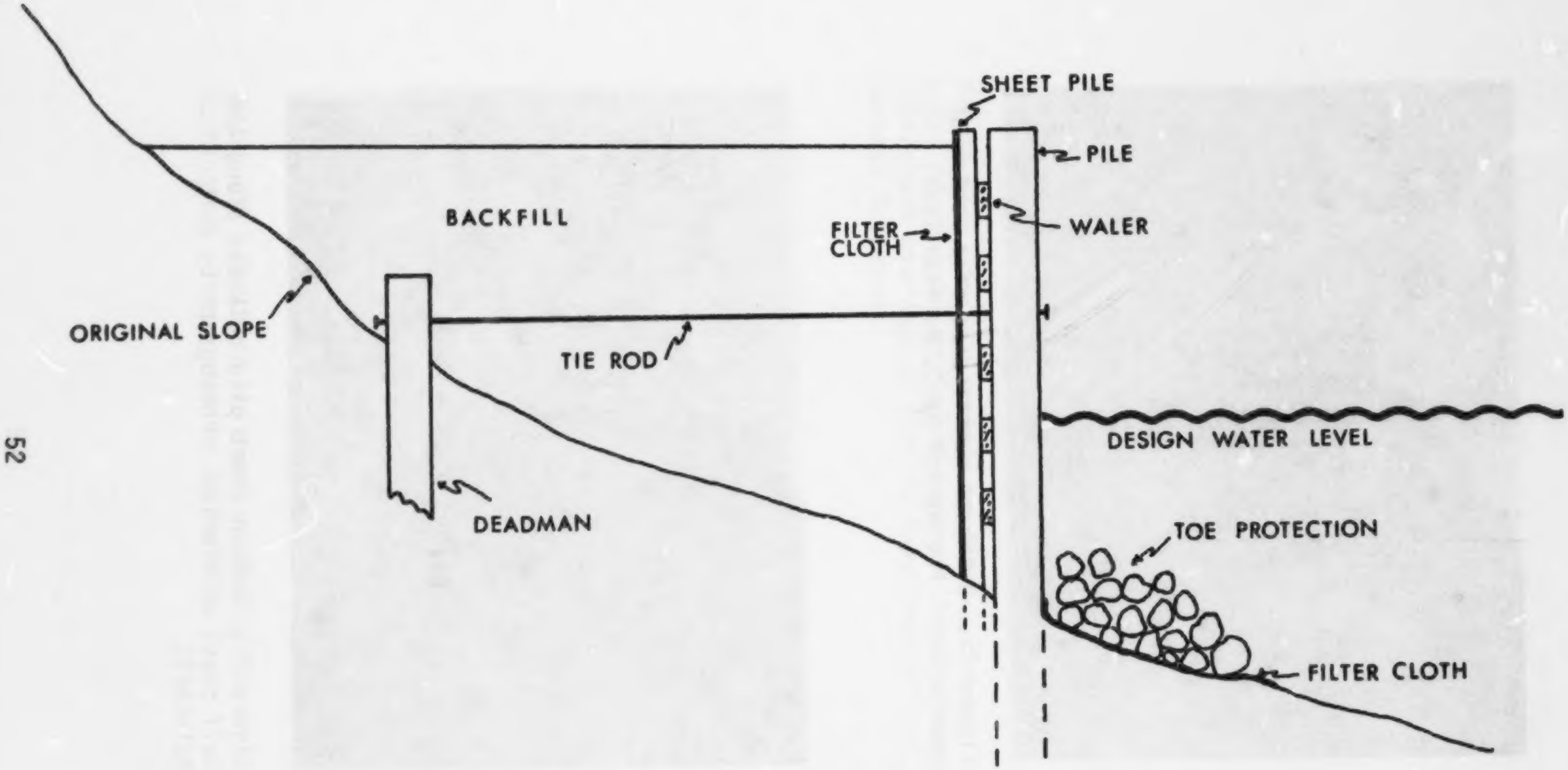

SHEET PILE
PILE
WALER
FILTER CLOTH
BACKFILL
ORIGINAL SLOPE
TIE ROD
DEADMAN
DESIGN WATER LEVEL
TOE PROTECTION
FILTER CLOTH

Figure 27. Side view of a typical sheet pile bulkhead. Dimensions and details to be determined by particular site conditions.

timber. Tie rods (sometimes referred to as tie backs) when made of steel cable should be coated or wrapped to prevent corrosion (Collier 1975). Tie rods function to prevent seaward tipping of the bulkhead and must be securely anchored. Anchors typically are deadmen (horizontally placed timbers), anchor piles,or concrete anchor blocks.

Construction materials used for toe protection and filters are similar to those used for revetments.

Expected Life Span

The expected life span of bulkheads ranges from 10 yr to approximately 30 yr. Life span is site specific and will depend upon location of the structure on the beach, design wave height and period, construction materials, and climatic conditions.

Timber and steel sheet pile bulkheads have shorter life spans in warmer climates. Deterioration of wooden structures from decay, insects, and marine borers is accelerated, as is the corrosion of steel structures. Collier (1975) related one instance in Florida where a temporary wood work trestle, built from 450 untreated pine piles, was rendered unsafe for work after only 3 mo of service due to shipworms. The life span of steel structures may be less than 10 yr in warm marine environments if the steel is not coated or of a resistant chemical composition (Collier 1975).

Very little data are available to assess the actual durability of various bulkhead types. However, several authors have pointed out that bulkheads do not provide a long-term permanent solution to shoreline erosion because the beach will continue to recede (Coastal Plains Center for Marine Development Service 1973, U.S. Army Corps of Engineers 1964, 1971b). This recession may even be accelerated as a result of wave reflection from the bulkhead(Figure 28).

Summary of Physical and Biological Impacts

Construction effects. Construction of sheet pile bulkheads involves transporting materials to the site, driving or jetting piles and sheet piles, placing and securing tie rods and anchors, and backfilling behind the bulkhead. These activities require a truck for material transport, a bulldozer, a pile driver or pile jetting equipment,a crane for lifting heavy piles, anchors, and walers, and dredging equipment if fill material is obtained by dredging. Other types of bulkheads require similar equipment.

This heavy equipment causes noise and air pollution at the site. Carstea et al. (1975a) maintain that air pollution, resulting from construction of a 150 ft (45 m) timber bulkhead, should be well below Federal air quality standards and that noise will have an effect on areas within about 200 ft (61 m) from the site. However, construction noise may be sufficient to disrupt waterfowl which may be nesting or resting at or near the site.

Fish and wildlife habitat is disrupted and/or lost due to construction activities. Damage to fish and wildlife resources depends upon the type of habitat in the area prior to construction, where the structure is placed on the shoreline, its size, and construction methods. The bulkhead and associated backfilling bury established terrestrial and intertidal flora and fauna. The heavy equipment used during construction disturbs vegetation behind the structure (Knutson 1977). In areas where bulkheading and backfilling are used to create shorefront real estate, bulkhead construction impacts represent the first step in a chain of events which lead to larger losses due to land development behind the bulkhead. Benthic habitat, in addition to terrestrial and intertidal habitat, is also lost if dredging is used to obtain fill material or to create a channel up to the bulkhead.

Construction activities will cause local erosion and new sediment deposits in the vicinity of the bulkhead due to disturbance of bottom sediments during dredging, pile driving or jetting, and backfilling. New sediment deposits are often silty and can destroy spawning areas, smother benthic organisms, and reduce bottom habitat diversity and food supply (Carstea et al. 1975b).

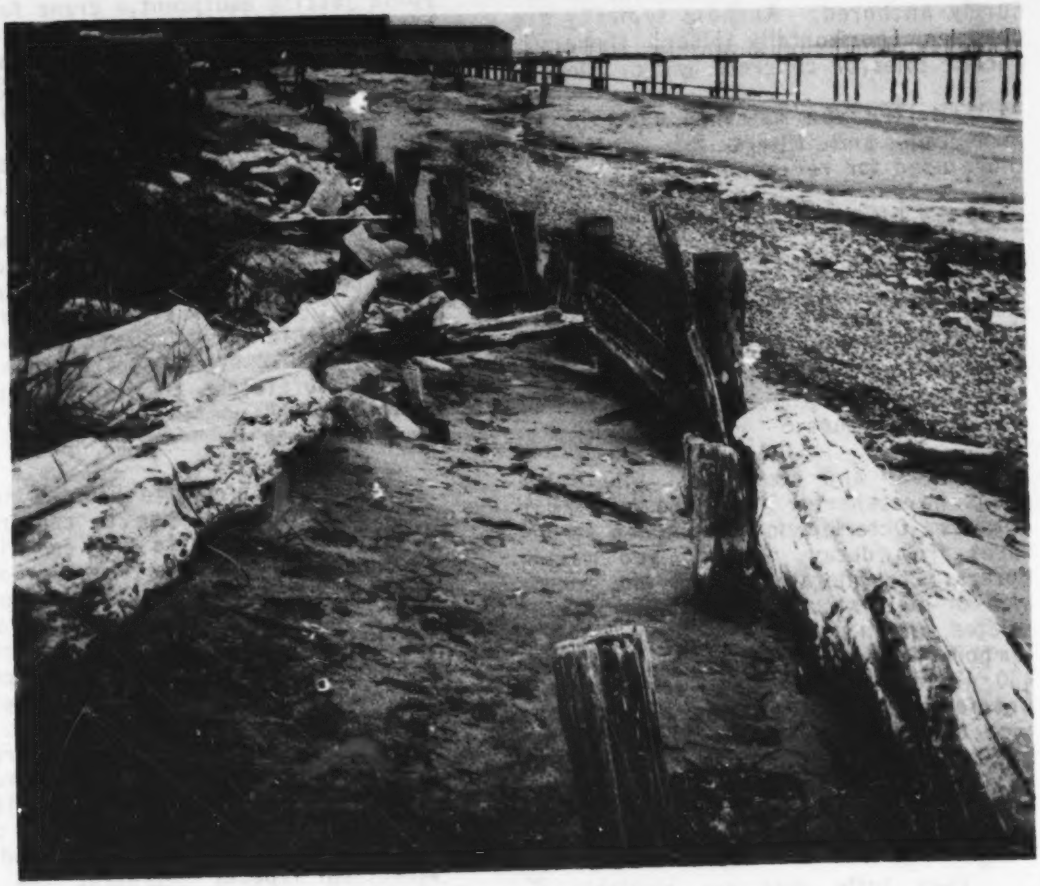


Figure 28. Old bulkhead line on a beach that has continued to erode in Skunk Bay, Washington. Photograph by C. A. Francisco.

Several authors have pointed out that disturbance of substrate and erosion during bulkhead construction leads to turbidity and water quality degradation (Boberschmidt et al. 1976, Carstea et al. 1975a, 1976, Environmental Quality Laboratory, Inc.1977, Gantt 1975, U.S. Army Engineer District, Baltimore 1975,Virginia Institute of Marine Science 1976). However, biological impacts from turbidity and changes in water quality have not been well documented. Construction activities which cause the greatest increases in turbidity are dredging and filling, and pile driving or jetting. Resuspension of bottom sediments from these and other construction activities may release trapped nutrients, heavy metals,and other toxic substances into the water. Suspended sediments reduce light penetration which may lead to a temporary decrease in primary productivity. Suspended materials also may interfere with respiratory and feeding mechanisms of the fishes, zooplankton, and benthic organisms.

Chronic effects. Bulkheading has often been described as a relatively impermanent means of separating land from water, especially in areas where the shoreline is eroding (Coastal Plains Center for Marine Development Service 1973, U.S. Army Corps of Engineers 1964, 1971b, Warnke 1973). Bulkheads, like revetments, protect upland areas directly behind the structure from the eroding action of waves and currents. However, they do not protect adjacent beaches or the foreshore.

A bulkhead often promotes erosion of the foreshore (Bauer 1975, Bruun and Manohar 1963, Coastal Plains Center for Marine Development Service 1973, King 1972, Massachusetts Coastal Zone Management Program undated a, Pallet and Dobbie 1969, Schultz and Ashby 1967, Slaughter 1967, U.S. Army Corps of Engineers undated). Erosion of the foreshore is caused by an increase in wave energy due to waves reflecting off the face of the structure (Figure 21).

Foreshore erosion is particularly severe during storms. Damage inland from hurricanes and storms often is increased due to replacement of energy absorbing tidal marshes with impermeable bulkheads (Gosselink et al. 1973, King 1972). A bulkhead restricts movement of sand to and from beach and dune areas (Georgia Department of Natural Resources 1975, Gifford 1977). This, coupled with ongoing reflected wave energy from bulkheads, inhibits the recovery of sediments to storm eroded beaches.

Bulkheads may also promote erosion of adjacent beaches (Bellis et al. 1975, Carstea et al.1975a, Gantt 1975, Georgia Department of Natural Resources 1975, Herbich and Schiller 1976, Pallet and Dobbie 1969,U.S. Army Engineer District, Baltimore 1975). Erosion of adjacent beaches may be accelerated until a new geohydraulic equilibrium is reached. This erosion may result from alterations in water circulation patterns or from the structure intruding into the littoral zone and obstructing littoral drift (Bauer 1975, Carstea et al. 1975a, Gantt 1975, Georgia Department of Natural Resources 1975).

Bulkheads, like revetments, can affect the plant and animal communities in the upper foreshore and backshore zones. Bulkheads, constructed in wetland areas, can cause extensive damage to fish and wildlife habitat. Construction and associated backfilling destroy wetlands by covering up narrow fringe marshes, by covering up the waterfront edge, and by altering water circulation in larger shorefront marshes. Wetlands are highly productive areas which filter upland runoff and function as nutrient and sediment traps. Destruction of shorefront wetlands eliminates waterfowl feeding, nesting, and resting habitats and destroys the habitat for other birds, reptiles, and small mammals (Boberschmidt et al. 1976, Carstea et al. 1975a, Herbich and Schiller 1976).

The construction of a bulkhead eliminates much of the intertidal zone. If the structure is built below the mean high waterline, it eliminates the transition zone between the intertidal and adjacent subtidal areas. This region is the most productive zone in estuaries (Lindall 1973, Odum 1970, Stockley 1974). This transitional zone, replaced with a vertical bulkhead, provides little productive habitat. At most a wooden bulkhead provides a new habitat for a few sessile and marine boring organisms, such as barnacles, hydroids, gribbles, and shipworms.

The newly created deep water zone in front of a bulkhead often has a lower concentration of detritus, lower phytoplankton production, and fewer benthic organisms than adjacent unbulkheaded areas (Massachusetts Coastal Zone Management Program undated b, Odum 1970). The turbulence and scouring action in front of bulkheads from reflected wave energy often prohibits vegetation from reestablishing (Gantt 1975, Knutson 1977) and may destroy existing grass flats (Gifford 1977).

Ellifrit et al. (1972) studied clam populations in bulkheaded and adjacent natural areas in Hood Canal, Washington. Twice as many clams were found on natural beaches at three out of the four sites studied. At two sites significantly more Japanese littleneck clams, Venerupis japonica, were found in upper intertidal regions. Differences in size and distribution were noted. Clams in the lower intertidal regions appeared unaffected by bulkheads. The authors concluded that these differences probably were due to changes in current patterns associated with bulkheads. Bulkheads appeared to produce less favorable conditions for settling and survival of clam larvae and may have caused reduction in availability of nutrients and food.

Moore and Trent (1971) studied settling,growth,and mortality of oysters in two areas in West Bay, Texas. The first area was a dead end canal that had been created by dredging, bulkheading, and filling of a coastal marsh. The second area was a dead end bayou in an unaltered part of the same marsh. The settling of oysters was 14 times greater in the natural marsh than in the canal area. Faster growth rates and lower annual mortality rates characterized oysters in the natural marsh. The authors attributed these differences to the poor water circulation, plankton blooms, low levels of dissolved oxygen, and high nutrient levels in the canals.

Studies of shrimp in bulkheaded and natural estuarine habitats have shown natural areas to be more productive (Mock 1966, Trent et al. 1976). These differences have been attributed to low abundance of organic detritus and benthic macroinvertebrates, deeper water, and loss of intertidal vegetation in bulkheaded areas.

Bulkheads also can affect fish spawning, feeding, and nursery habitat. For example, bulkheads have been shown to alter salmon fry behavior in Puget Sound, Washington (Heiser and Finn 1970, Stockley 1974). Vertical bulkheads cause an abrupt habitat change with few shallow water areas. Salmon fry tend either to go out into deeper water when confronted with a bulkhead or to concentrate near bulkheads and not go around them. Both circumstances make salmon fry extremely vulnerable to predation. Stair-step design bulkheads or riprap revetments on a 45 or less degree angle were found to provide protective habitat for salmon fry (Heiser and Finn 1970). In another study, (Millikan et al. 1974) bulkheads extending down below the mean high waterline were found to bury and destroy smelt spawning substrate in Puget Sound and Hood Canal, Washington. As a result of this study, State bulkhead criteria for surf smelt spawning beaches were modified to protect upper intertidal and sand-fine gravel beach areas.

Cumulative effects. Physical and biological impacts from the construction of a number of bulkheads in a coastal area may have a cumulative effect, however, no pertinent studies were found. Irregular alignment and patchy bulkheading along a shoreline often create erosion pockets between bulkheads on natural beaches (Bauer 1975). Extensive bulkheading of wetlands on the shores of estuaries and bays can severely reduce fish and wildlife habitat and impact estuarine related fisheries of a whole region, as well as waterfowl populations. For example, Lindall (1973) identified bulkheading of south Florida's estuarine shorelines and the resulting destruction of the nursery grounds as a threat to the estuarine-dependent fisheries (about 85% of the area's commercial fisheries) of that region. Clearly, examination of the physical and biological impacts of bulkhead construction on a case-by-case basis ignores a host of potential cumulative physical, chemical, and biological impacts (Fetterolf 1976).

Structural and Nonstructural Alternatives

The design of bulkheads can be altered, or they can be used in conjunction with other structures, to modify their impact. Bulkheads can be stepped back in a series of low vertical walls which will provide some variation in depths in front of the structure. When enough steps are provided, the structure becomes a revetment. (There is no exact definition which differentiates a stepped bulkhead from a revetment.) Another alternative is to use a bulkhead landward of mean high water to protect uplands from higher wave conditions and use a sloping revetment or vegetation to protect the foreshore or intertidal area.

The alternatives must correspond to the intended function of the structure. If the function of the bulkhead is to protect the backshore land area and prevent sliding, an alternative structural solution is to build a revetment. Offshore breakwaters can also be used to reduce the wave attack on the land. Building up the beach (to protect the uplands) by groins or beach nourishment is also an alternative to bulkheads. Another alternative is to let the land erode and move or abandon upland structures. (See also Revetments.)

If the bulkheading is needed to achieve a vertical interface between water and land, then alternatives must respond to the need for the vertical interface. If the vertical face is for mooring vessels, the same function can be achieved by building a pier at right angles to the shore or placing mooring buoys offshore. If the vertical interface is needed for recreational or aesthetic purposes (to allow people to get close to the water), a pier or structure projecting into the water presents a logical alternative.

The predominant criticism of bulkheads relates to their vertical design and the consequent loss of variable depths and intertidal zones which exist on natural shorelines. The alternatives which best protect these features are either beach nourishment to maintain a natural-like shoreline or revetments. A revetment will provide protection to a specific site and, if designed properly, will allow variable depths and intertidal zones to be retained.

Regional Considerations

Along the north Pacific coastline (Coastal Region 1), bulkheading is most frequently encountered in Puget Sound. Bulkheads have been shown to alter salmon fry behavior in Puget Sound, Washington, and in the Columbia River estuary (Heiser and Finn 1970, Stockley 1974). Vertical bulkheads often eliminate shallow water regions, and salmon fry behavior in the vicinity of such structures makes them extremely vulnerable to predation. Stair-step design bulkheads or riprap revetments on a 45 or less degree angle were found to provide protective habitat for the salmon fry (Heiser and Finn 1970). Another concern in Puget Sound and vicinity is the destruction of surf smelt spawning habitat by bulkheading spawning beaches. State bulkhead criteria for surf smelt spawning beaches were recently modified to protect upper intertidal sand-fine gravel beach habitat (Millikan et al. 1974).

Bulkheads built at the bottom of sea cliffs are one attempt to control cliff erosion in southern California (Coastal Region 2). They frequently are found in conjunction with small boat harbors in this region. Areas of the Gulf of Mexico (Coastal Regions 3 and 4) have been extensively bulkheaded. In Mississippi, from Biloxi Bay westward, including the eastern half of Hancock County, the entire shoreline has been altered by bulkheading and artificial beach nourishment (Virginia Institute of Marine Science 1976). Bulkheads are also prevalent along the Atlantic coast (Coastal Regions 6 and 7). They are found almost continuously along northern New Jersey shorelines (Yasso and Hartman 1975).

A common practice in Galveston Bay, Texas, and in southern Florida (Coastal

Regions 3, 4, and 5) has been to build bulkheads along vegetated shorelines and then to backfill the area to create waterfront real estate (Lindall 1973). The natural shoreline is usually altered by channelization, bulkheading, and filling. Houses are built on narrow strips of land which are separated by a series of dead-end channels (hence the name "finger-type" development). The biological effects of this type of development in bays and estuaries have not been well researched. However, several studies do give some indications of potential impacts. Physical changes in estuaries and bays include: reduction in acreage of shore and marsh vegetation, changes in marsh water circulation patterns and nutrient input into the bay or estuary, changes in water depth and substrates, and the conversion of aquatic areas to upland areas with a resulting decrease in water area in the bay or estuary (Corliss and Trent 1971, Cronin et al. 1971).

The ecology of one finger-type housing development in West Bay, Texas, has been studied extensively. Phytoplankton production (Corliss and Trent 1971, Trent et al. 1976), substrates, and hydrology (Trent et al. 1976)were studied in an open bay area, in a bulkheaded canal area in the development, and in an adjacent natural marsh area. In general, productivity was higher in the marsh than in canal areas and lowest in the open bay. The plankton blooms followed by low levels of dissolved oxygen, high nutrient levels, fish kills, and lowered production of oysters, benthic macroinvertebrates, and shrimp in summer months indicated the presence of eutrophic conditions in the canal areas of the housing development. Similar eutrophic conditions have been reported in housing developments in Florida (Lindall 1973, Taylor and Saloman 1968). Trent et al. (1972) noted that standing crops of benthos, fish, and crustaceans were relatively high in the canal areas in spite of apparent eutrophic conditions. The authors were unsure if this was due to canal areas in the housing development being self-supporting in terms of vegetative production or whether productivity relied upon the detritus carried in from the adjacent marsh by tidal action.

REVETMENTS

Definition

A revetment is a sloped structure built to protect existing land or newly created embankments against erosion by wave action, currents, or weather. Revetments are usually placed parallel to the natural shoreline. Riprap (randomly placed stones) and gabions (a wicker-like basket which can be filled with stones) can be included in this definition.

Structure Functions

The primary function of most revetments is to protect the area landward of the revetment from erosion or scour due to waves or currents. This protection is due to the armoring characteristics of the revetment and its ability to dissipate wave energy. Revetments are normally used where it is necessary to retain the shore in a more seaward position relative to adjacent lands, where there is little or no protective beach in front of the land to be protected, or where it is desired to maintain a certain depth of water in front of a structure. Revetments are especially useful at the mouths of waterways where erosion is frequently severe (Coastal Environments, Inc. 1976). They may also prevent undermining from wave erosion when placed along the seaward slope of eroding dunes or cliffs (Yasso and Hartman 1975). Revetments are often used to protect the foundations of structures, such as bulkheads or buildings (Figure 29), from erosion. Figures 30 and 31 give examples of riprap and concrete revetments. Revetments are generally used where there is the potential for high wave energy. Bulkheads can function in a similar capacity, but offer far less energy dissipation.

Site Characteristics

Revetments are generally built to protect eroding shorelines. They are found in many types of coastal habitats including areas with eroding embankments or cliffs and little or no protective beach. Their most common occurrence is in developed areas where the shorefront property is endangered by erosion.

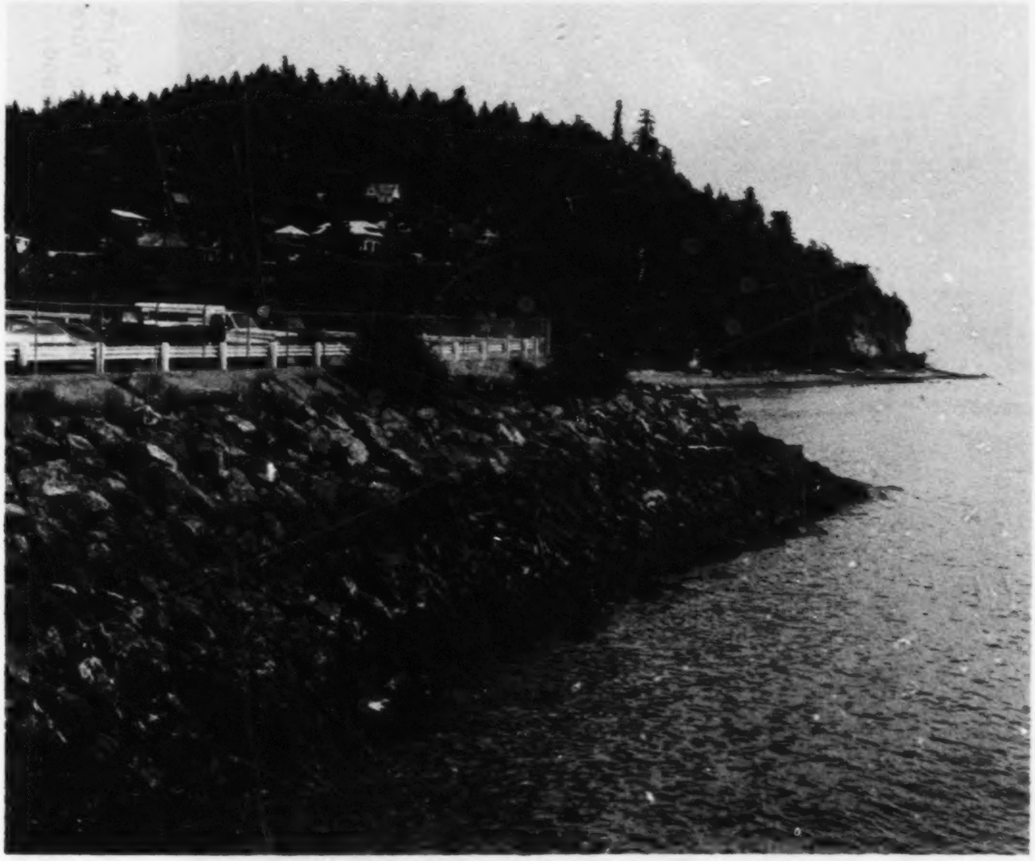


Figure 29. This riprap revetment functions to limit erosion of the parking lot at the Kingston, Washington, ferry terminal. Picture was taken at low tide. Light and dark colored bands on the revetment are due to biological zonation. Photograph by C. A. Francisco.

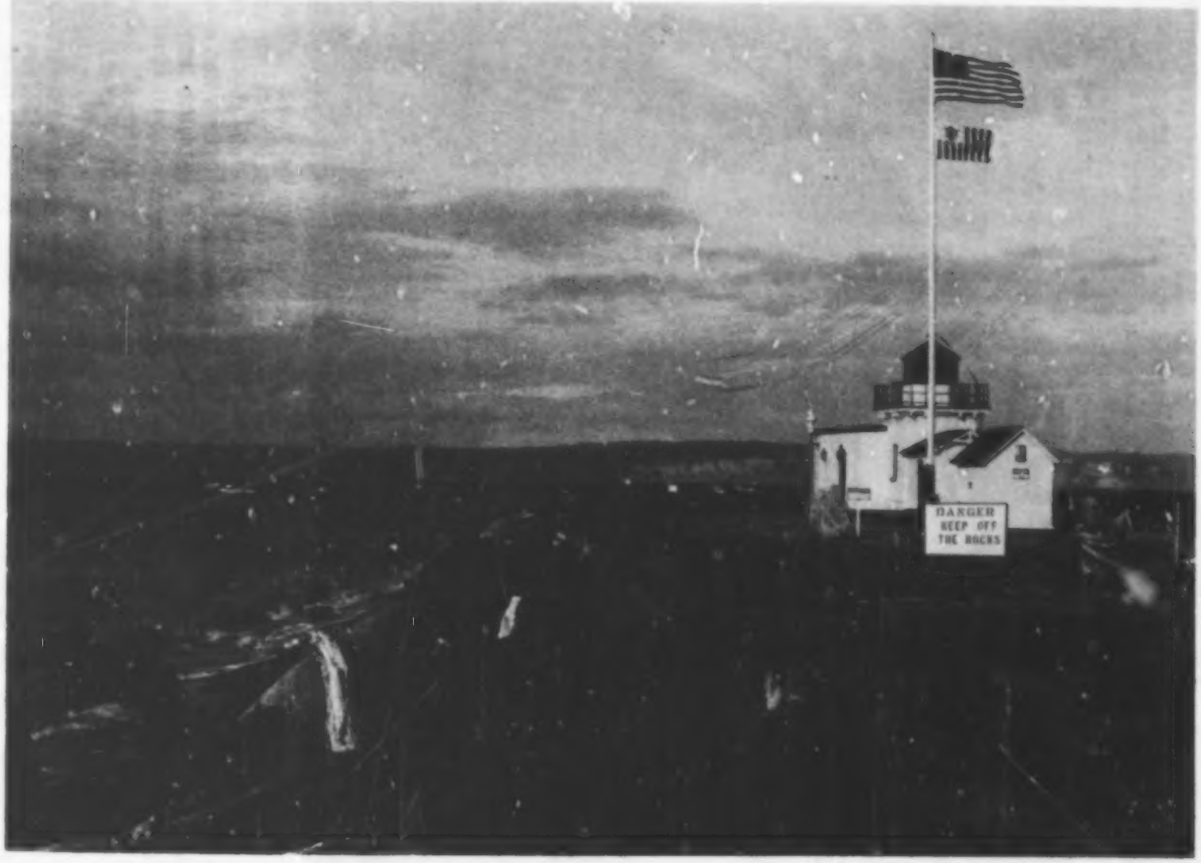


Figure 30. Riprap revetment protects the U.S. Coast Guard Light Station at Point No Point, Washington. Large drifting logs, such as the ones pictured in the foreground, make the use of gabion revetments impracticable in much of Puget Sound. Photograph by C. A. Francisco.

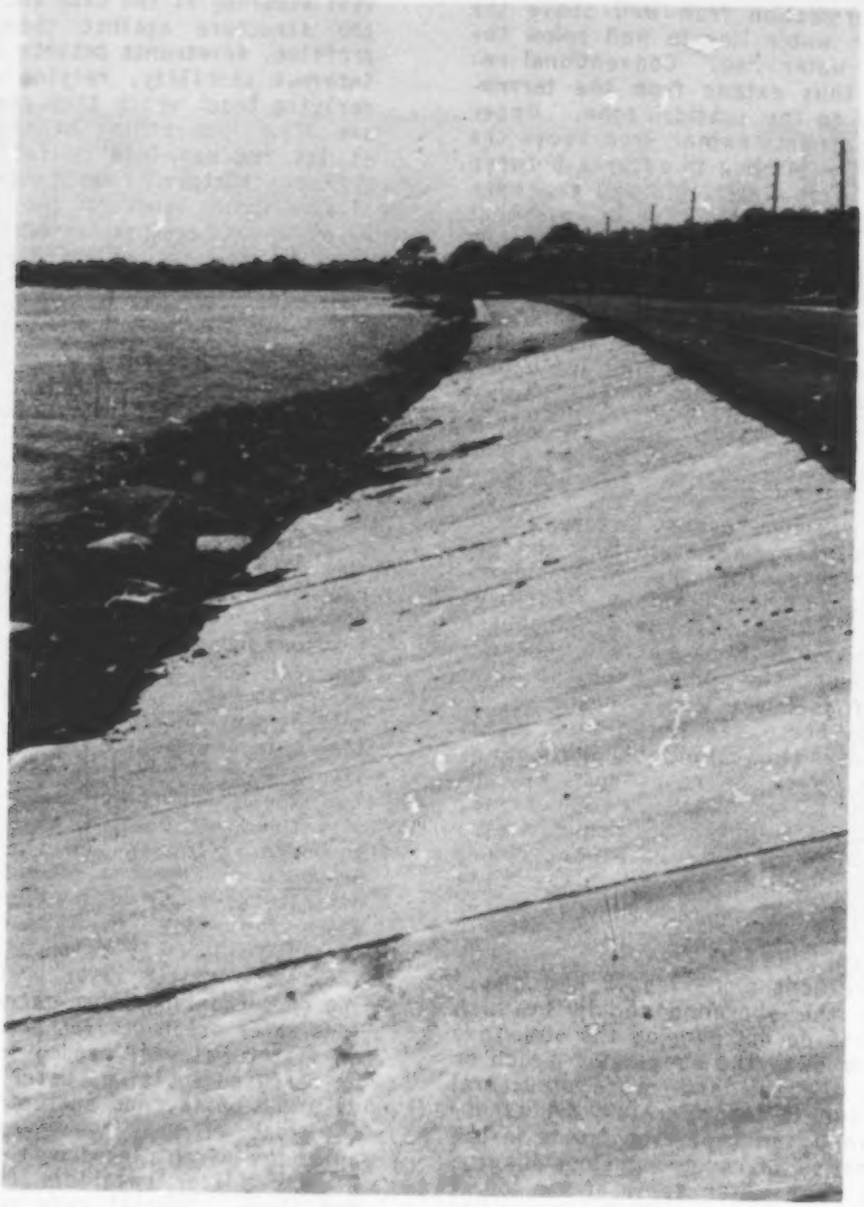


Figure 31. Concrete revetment along U.S. Highway 98 in the vicinity of Port St. Joe, Florida. Note the toe protection at the base of the revetment. Photograph by E. L. Mulvihill.

Conventional revetments typically provide protection from well above the mean high water line to well below the mean low water line. Conventional revetments thus extend from the terrestrial zone to the subtidal zone. Upper beach revetments extend from above the mean high water line to an area between the mean high water line and the mean low water line. This type of revetment generally lies within the region extending from middle intertidal zone to the terrestrial zone. Revetments can also be used entirely above the mean high water line for protection against storm generated tides. Revetments are usually constructed parallel to the natural shoreline.

Placement Constraints

Engineering. Several factors should be considered when evaluating the design of a revetment. Design considerations include design life of structure, design wave, seasonal changes in beach profile, water level range (e.g.,changes due to tides, storms, and for the Great Lakes seasonal lake level), beach composition,and beach use (McCartney 1976). Once these site conditions are known, alternate types of revetments may be evaluated. Armor facing requirements, wave runup heights, toe scour depth, toe protection needs, revetment slope, revetment length, and filter requirements vary with different types of revetments.

Revetment slope length and placement on the shoreline should be such that waves do not overtop the structure and erode away the supporting beach or saturate the soil and cause structural failure due to the hydraulic processes. Wave runup, an important factor in the determination of revetment slope length, depends upon water depth at the toe of the structure, slope of the beach in front of the structure, and the slope, shape, roughness, and porosity of the revetment (U.S. Army Corps of Engineers 1973b, McCartney 1975). Other factors which determine revetment slope length include water level range, beach slope, toe scour depth, and minimum water depth allowed at the toe of the structure (McCartney 1976).

Toe protection is necessary to prevent scouring at the base and to protect the structure against changing beach profiles. Revetments possess very little internal stability, relying on the underlying beach which they protect (Figure 32). Undermining of the structure at its toe can lead to failure of the entire structure. Wave energy is deflected both landward and seaward as waves break against revetments. Wave energy which is deflected seaward can cause scouring of material at the foot of revetments (U.S. Army Corps of Engineers 1973b). Factors affecting the amount of toe scour include slope, permeability and roughness of the revetment, water depth, hypothetical surface of wave reflection, wave height and steepness,and beach sand size (McCartney 1976, Sato et al. 1968).

In general, rougher, flatter, and the more permeable revetment surfaces cause less toe scour and require less toe protection. Structural failure due to scour may be avoided by incorporating adequate toe protection into the design of revetments. Common toe protection methods are addressed in the construction materials section.

The supporting materials under structures may also be washed away if an adequate filter is not used. A filter prevents undermining of the revetment, distributes armor unit weight, and provides for relief of hydrostatic pressures (Collier 1975, McCartney 1976). Ideally, a filter layer prevents scouring of supporting shore material and allows water drainage. The amount and type of filter material needed is determined by beach composition, water depth, type of armor units, and current velocities. In areas of heavy wave action, armor units are often placed on a scour pad of plastic filter material (filter cloth) and stone. Special care must be taken in design and construction of impermeable revetments to prevent excessive landward hydrostatic pressure. Designing the structure with gravel or with rock weep holes are ways to help prevent this potential problem (McCartney 1976).

Materials used for armor facings should be designed to remain intact

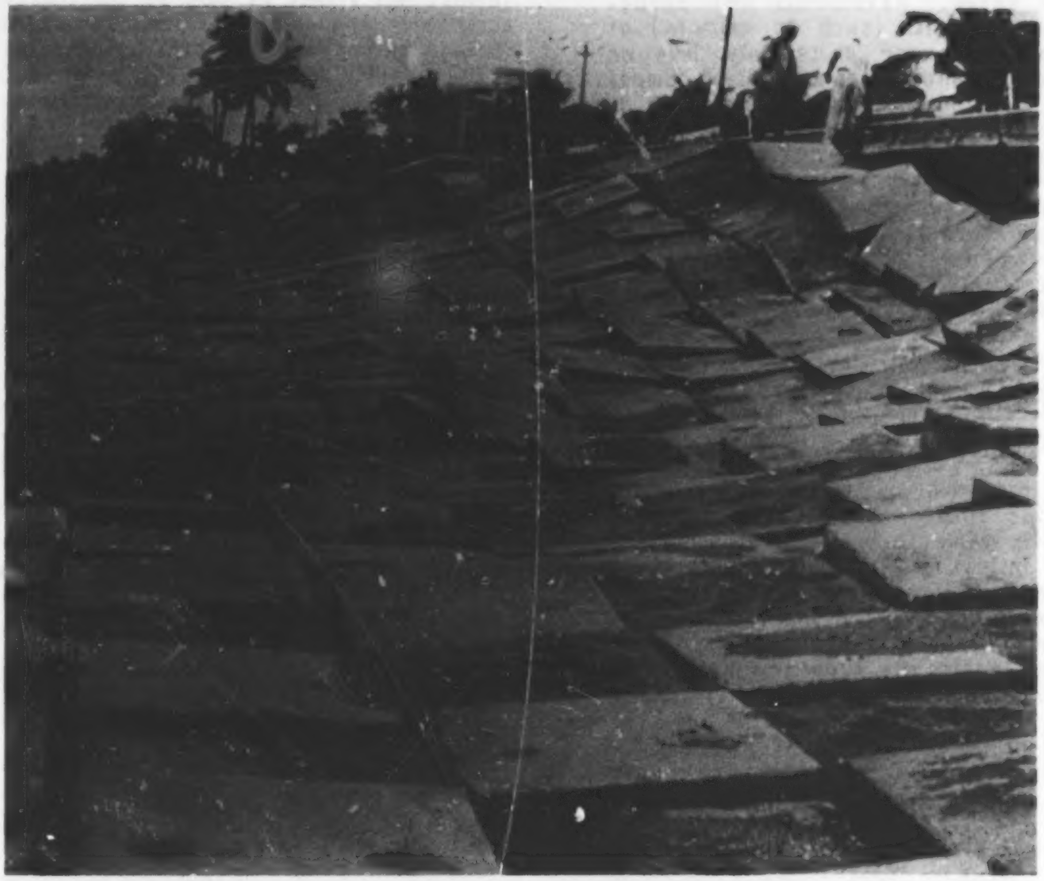


Figure 32. Failure of this interlocking concrete block revetment was primarily due to settling and erosion of supporting beach material. Due to its flexibility, this structure still affords some protection. Photograph courtesy of Florida Department of Natural Resources.

under anticipated environmental conditions. Armor facings constructed of materials such as riprap or rubble should have components which are dense and heavy enough not to be moved by waves. Revetments with permeable armor units (such as gabions) or interlocking armor units rely less on mass of the individual structural components to withstand wave energy than do more solid type revetments (Docks and Harbor Authority 1965). More detailed discussions of the various types of armor units, their advantages and disadvantages, are found in the Shore Protection Manual (U.S. Army Corps of Engineers 1973b) and the Survey of Coastal Revetment Types (McCartney 1976).

Socioeconomic. Social and economic considerations can affect the location and type of structure built at a site. Local laws, costs of structural alternatives, historical points of interest, current and future uses of the area, and aesthetic values are some of the criteria which influence the placement of a revetment. Current and future uses of an area help to determine the need for a revetment at a given location. Beach use influences the type and location of the structure on the shoreline.

The design life of a temporary revetment to protect an exposed embankment during construction activities would be shorter than the design life of a revetment built to protect a shorefront dwelling from damage due to beach recession. Revetments can severely affect waterfront recreational activities, such as swimming, boating, and shell-fishing. McCartney (1976) points out that a beach used "for recreation and other purposes may dictate use of upper beach revetment to contain runup and sandfill on the beach face seaward of the revetment."

Several authors have commented on the visual impact revetments have on the shoreline. Structures which resemble and follow the natural shoreline seem to have less adverse impact on the scenic or aesthetic values of an area. For example, gabions are sometimes viewed as a more aesthetically pleasing type of revetment than either brickwork or concrete slabbing because of their resemblance to the natural stonework (Docks and Harbor Authority 1965). A rock revetment which was to be built at Sunset Cliffs, San Diego County, California, was viewed as more aesthetically acceptable than a more formal structure (U.S. Army Engineer District,Los Angeles 1970). Bellis et al. (1975) point out that "the availability of 'free' materials such as demolished buildings, old tires, junked cars, and other debris all too often leads to really bizarre shorelines..." An example of such a shoreline is found in Figure 33. Some authors, however, view any type of revetment as an artificial intrusion that is an aesthetic affront to the shore environment. Bauer (1975) made the following comment with reference to riprap revetments:

> "The most negative feature of riprap, however, resides in the offending visual impact and environmental degradation of the shore resource. The use of such rock heaps, just as in the case of the streambank revetments, has now mushroomed into a serious shore despoilage - a syndrome that is lining our beautiful beach environments with ugly, incompatible borders and backdrops of rubble."

Economic feasibility often determines the number and types of structural alternatives available for a given location. Initial construction and maintenance costs for the design life of the project vary depending upon site conditions, geographic region, and materials used. Initial construction costs can range from $25.00 to $200.00 or more per linear foot of protection. While revetments tend to be less expensive than bulkheads, those constructed along the open coasts or to protect barrier beaches are expensive to build and maintain relative to those built in semiprotected and protected environments. Local availability of the suitable construction materials influences cost of the structure. The cost of maintenance depends upon the labor expenses, material costs and frequency of repair. For example, nylon bag and polyethylene tube revetments are relatively inexpensive to install, but may be expensive to maintain.

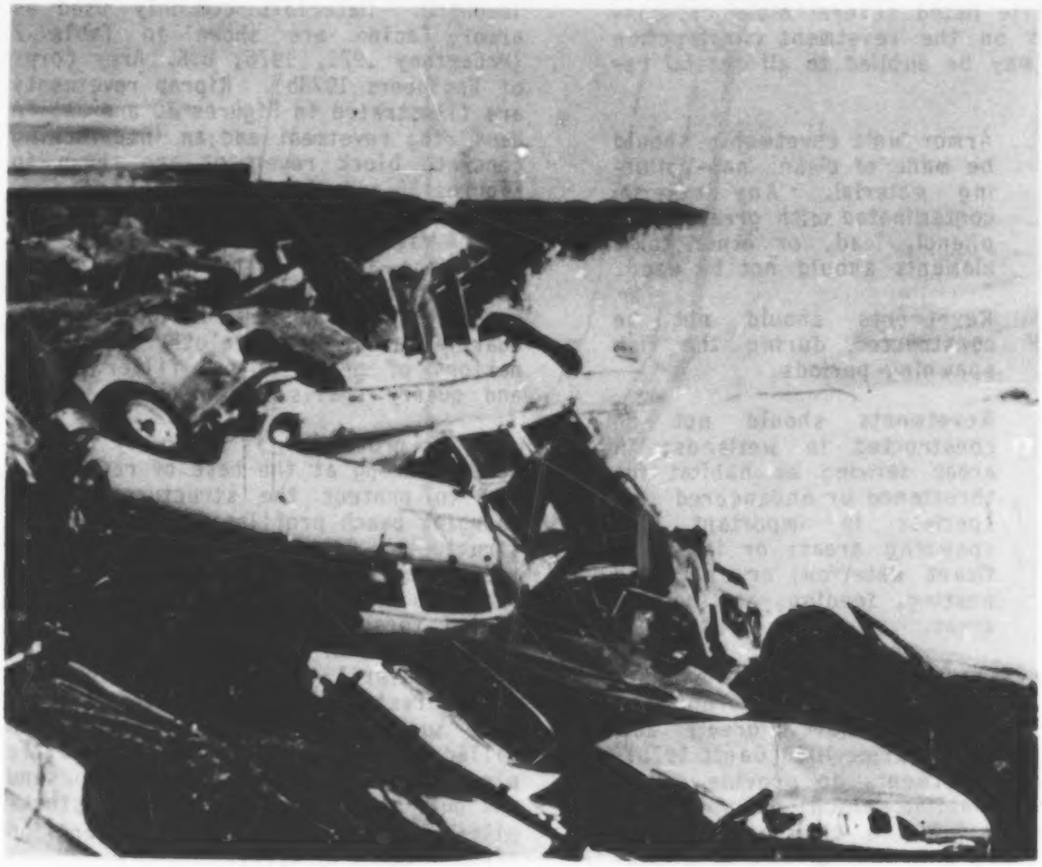


Figure 33. Pictured is a junk car revetment in Florida. Due to corrosion, the life span of car body revetments generally is less than 5 years in brackish water. There are also aesthetic considerations regarding this type of revetment. Photograph courtesy of Florida Department of Natural Resources.

Sandbags and tubes may easily be cut open by vandals (Marks and Clinton 1974) and deteriorate quickly, thus requiring frequent repair.

Biological. The Buffalo Army Engineer District (U.S. Army Engineer District, Buffalo undated a) in issuing a general permit for shore protection in Lake Erie listed several biological constraints on the revetment construction which may be applied to all coastal regions:

- Armor unit revetments should be made of clean, non-polluting material. Any material contaminated with grease, phenol, lead, or other toxic elements should not be used.
- Revetments should not be constructed during the fish spawning periods.
- Revetments should not be constructed in wetlands; in areas serving as habitat for threatened or endangered species; in important fish spawning areas; or in significant waterfowl or shorebird nesting, feeding, and resting areas.

Revetments with facings that are highly irregular (such as riprap) and have a shallow slope have a greater ability to support marine life (Gantt 1975). Although revetments do provide a new irregular habitat which does support greater marine life than vertical sea walls, there is an initial loss of organisms and habitat by placement of revetments.

Construction Materials

There are two structural classes of revetments (U.S. Army Corps of Engineers 1973b): rigid, cast-in-place, and flexible or articulated armor unit revetments. Rigid, cast-in-place types of revetments are constructed of cement, asphalt, or bitumen grouted stone. A concrete revetment is very effective against wave attack, but water must be removed from the construction area to pour the concrete. A concrete revetment is depicted in Figure 34. Components of armor unit revetments include an armor face, filter, and protective toe (McCartney 1976).

The armor face is the outer layer of the structure which serves to dissipate wave energy as waves are deflected landward. Materials commonly used as armor facing are shown in Table 2 (McCartney 1975, 1976; U.S. Army Corps of Engineers 1973b). Riprap revetments are illustrated in Figures 30 and 31. A Nami ring revetment and an interlocking concrete block revetment are shown in Figures 35 and 36.

A filter serves as an interface between the armor facing and the native soils which the structure protects. Some commonly used filters include gravel, quarry spalls, filter cloth, and combinations of gravel and a filter cloth, and quarry spalls and a filter cloth.

Toe protection is necessary to prevent scouring at the base of revetments and to protect the structure against changing beach profiles in front of the structure. Common types of revetment toe protection include aprons which will sag into any scour hole that develops, buried toes, toes weighted with extra layers of armor units (armor units are not necessarily the same as those used on the rest of the structure), flexible mats such as gabions or filter cloth filled with sand, bag or rock sills placed seaward of the toe to trap sand and bury the toe, sand or gravel stockpiles, cutoff walls, and anti-erosion rings (McCartney 1976).

Expected Life Span

The expected life span of revetments ranges from 5 to 30 yr or more. Expected life span will vary depending upon construction materials, the wave height and period the structure was designed to withstand, and the climatic conditions to which the structure is exposed. Damage to rubble-mound structures is generally progressive, and the Shore Protection Manual (U.S. Army Corps of Engineers 1973b) recommends considering both the frequency of damaging waves and

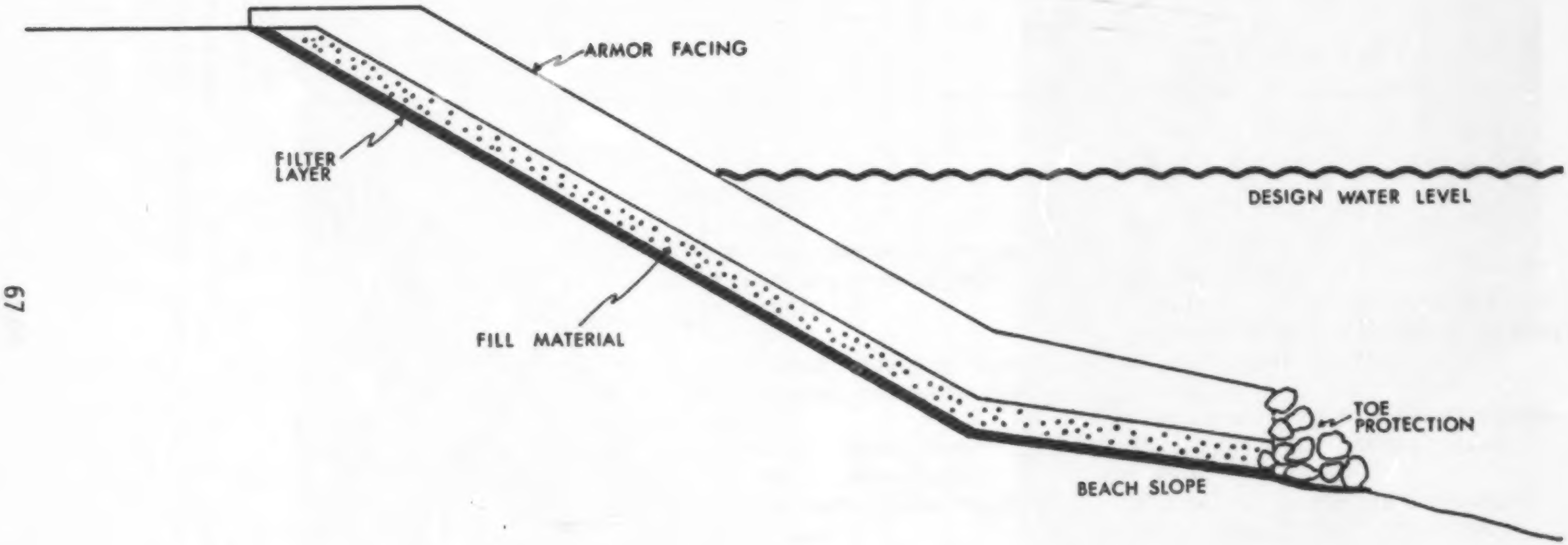

ARMOR FACING
FILTER LAYER
DESIGN WATER LEVEL
FILL MATERIAL
TOE PROTECTION
BEACH SLOPE

Figure 34. Profile of a revetment. Construction materials, dimensions and details are determined by particular site conditions.

Table 2. Types of revetment armor facings.

Natural materials	Manufactured units	Other materials
Riprap	Gabion (stacked or mat)	Rock overlaying a thin layer of asphalt
Uniform rock overlay	Woven wire fence mats filled with rocks, bricks, sandbags, etc.	Tires filled with sand cement
Vegetation	Cast concrete armor units (tribars, tetrapods, dolosses, quadripods, etc.)	Nylon fabric mat, bags, or tubes filled with concrete, sand, etc.
	Interlocking concrete blocks, (lok-gard, shiplap blocks etc.)	Stairstep sand cement lifts
	Gobi blocks	Fiberglass, steel, or aluminum mat
	Concrete cellular blocks	Nylon filter cloth
	Cinder or concrete building blocks	Rubble (dumped concrete, asphalt, bricks, building blocks, etc.)
	Nami rings	Automobiles

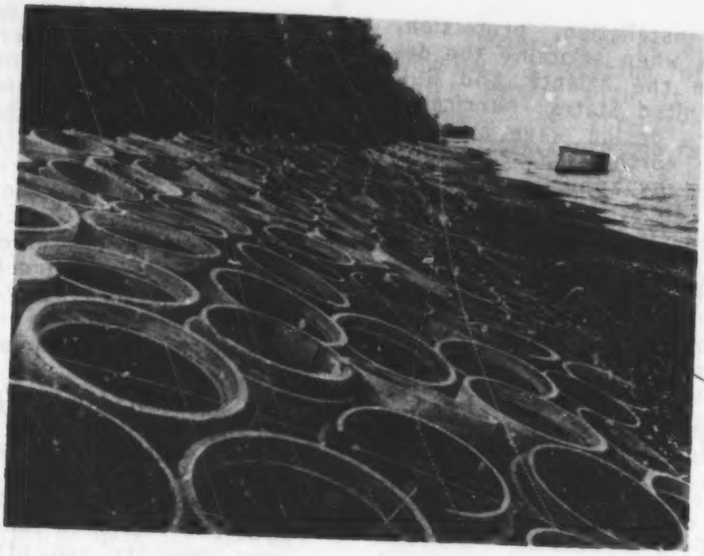


Figure 35. A Nami Ring revetment was constructed in 1974 at Little Girls Point on Lake Superior as part of the Michigan State Demonstration Erosion Control Program. Damage to this structure was extensive after two years of service. Photograph courtesy of the Michigan State Department of Natural Resources.

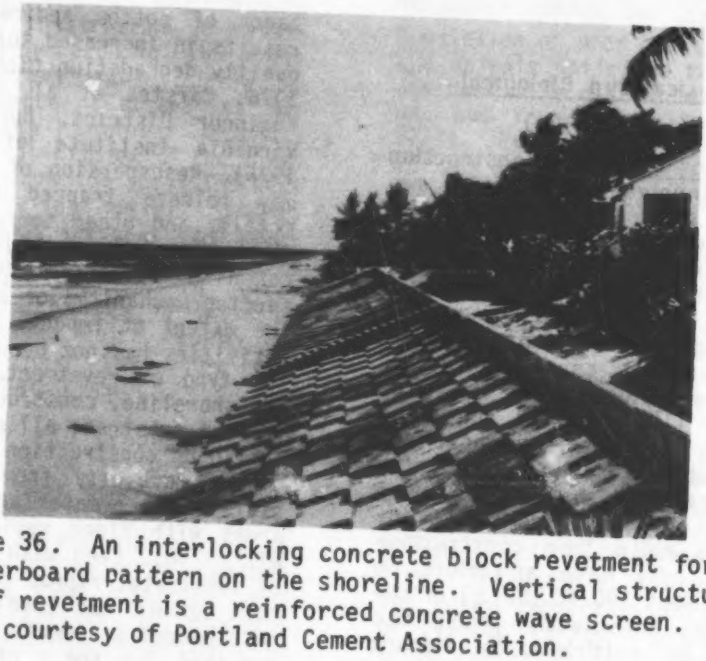


Figure 36. An interlocking concrete block revetment forms a checkerboard pattern on the shoreline. Vertical structure at top of revetment is a reinforced concrete wave screen. Photograph courtesy of Portland Cement Association.

the costs for installation, protection, and maintenance when selecting the design wave. On the Atlantic and Gulf coasts of the United States, hurricanes may provide the design wave criteria; whereas on the north Pacific coast, it may be provided by annually occurring severe storms (U.S. Army Corps of Engineers 1973b). It may not be economically feasible, however, to design a structure which will withstand a hurricane which may occur once every 20 to 100 yr. Structures located in areas with frequent storms should be built to withstand the storms and to avoid high annual maintenance costs. McCartney (1975) selected the relatively short design life of 5 to 10 yr for the upper beach revetments discussed in his study. This design life is economical and "compatible with erosion protection needs for high lake levels in the Great Lakes" (McCartney 1975). Gantt (1975) has described riprap revetments,if correctly designed and constructed, as being relatively permanent structures. However, very little quantitative data are available to assess the actual durability of riprap or other revetment types.

Summary of Physical and Biological Impacts

Construction effects. Construction of revetments involves transporting materials to the site, preparing the embankment to be protected, laying filter materials, placing armor units, and providing toe protection. These activities involve a truck for material transport and a front-end loader for construction. This heavy equipment causes noise, vibration, and air pollution at the site. Carstea et al. (1975a) noted that construction time is relatively short for structures such as riprap revetments. They also commented that air pollution is well below Federal air quality standards and that noise from construction activities will only have an effect on areas within about 100 ft (30 m) of the site. However, construction noise and activity may be sufficient to disrupt waterfowl which may be nesting or resting at or near the site. Construction activities also disrupt vegetation directly behind revetments (Knutson 1977).

Habitat is lost due to the structure being placed over the previously existing substrate (Gantt 1975). Established intertidal flora and fauna are often buried during the revetment construction (Coastal Plains Center for Marine Development Service 1973). All plant and animal communities from behind the revetment to beyond the revetment toe are therefore affected by the construction of revetments. However, in many cases, such as the construction of riprap revetments, a new and different type of habitat is created.

Construction activities will cause local erosion and new sediment deposits in the vicinity of the revetment (Ortolano and Hill 1972). This will occur from disturbance of bottom sediments and erosion of exposed substrate. New sediment deposits are often silty and can "destroy spawning areas, smother benthic organisms, and reduce bottom habitat diversity and food supply" (Carstea et al. 1975).

Several authors noted that disturbance of bottom sediments and erosion results in increased turbidity and water quality degradation (Boberschmidt et al. 1976; Carstea et al. 1975b; U.S. Army Engineer District, Buffalo undated a; Virginia Institute of Marine Science 1976). Resuspension of bottom sediments may release trapped nutrients, heavy metals, and other toxic substances into the water column. Suspended materials can also interfere with respiratory and feeding mechanisms of aquatic organisms. The extent of impacts from construction activities has not been well documented. The type of revetment, its location on the shoreline, construction methods, and type of substrate all play a role in determining construction effects. For example, turbidity from construction activities is greater and lasts longer in areas with finer sediments (Carstea et al. 1975a). Even with a fine grain type of substrate, riprap revetment construction should not lead to levels of the resuspended sediments which exceed those required for the protection of aquatic life (Carstea et al. 1975a). The effects of revetment construction must be evaluated in light of the duration of the construction period and the severity of disturbance.

Chronic effects. The presence of a revetment in an area leads to a number of physical and biological changes at the site and in the surrounding shoreline. A revetment, when adequately designed and constructed, will control erosion of the shoreline on which the structure sits; however, it will not stabilize adjacent beaches or the foreshore in front of the structure.

Alterations in the foreshore following revetment construction are site-specific and difficult to predict. Unlike the groins, revetments generally do not facilitate beach accretion in either the backshore or foreshore regions and may promote beach erosion in front of the revetment (Brater 1950, Michigan Sea Grant Advisory Program undated). Foreshore erosion, however, will be less from a revetment than if a bulkhead or seawall had been constructed because wave energy tends to be dissipated rather than reflected as waves run up revetment faces (Pallet and Dobbie 1969). In fact, construction of revetments on severely eroding shorelines can actually improve water quality by reducing turbulence (Carstea et al. 1975a, U.S. Army Engineer District, Buffalo undated a). Erosion of the foreshore can result from toe scour, increased backwash during severe storms (Brater 1950), and seasonal and long-term fluctuations in the beach profile in front of the structure. Gifford (1977) has noted bottom changes in front of revetments in Florida which usually involve deepening near the shore and parallel offshore bar formation.

Well-designed and properly placed revetments typically do not promote the beach growth as they offer very little obstruction to littoral drift. Poorly designed or placed revetments can cause increased erosion of adjacent beaches (Herbich and Ko 1968, Herbich and Schiller 1976). Erosion of adjacent beaches may result from alterations in water circulation patterns or from the structure intruding into the littoral zone and obstructing littoral drift (Carstea et al. 1975a, Gifford 1977).

Construction of a revetment is a physical alteration of the shoreline which brings with it many biological changes. The structure itself buries established flora and fauna. The revetment facing affords a new and different type of substrate. A revetment thus provides a new habitat for various terrestrial, benthic, and aquatic organisms. The plant and animal communities which colonize a revetment will have a community structure which is different from the one in existence prior to construction.

The diversity and abundance of organisms living in and around a revetment will vary, depending upon the type of revetment facing, energy conditions, its location on the beach, and the type of substrate on which the revetment was built. In some instances, a revetment can increase species diversity and abundance compared to what was previously in the area. An example of such an area is Rincon Island, an offshore man-made island in California which is protected by rock and tetrapod revetments. Rincon Island's revetments support a diverse population of over 225 species of plants and animals while the mainland, an area one-half mile distant with sandy beaches, has fewer than 12 species (Brisby 1977). Prior to construction, about 20 to 25 different species lived in the Rincon Island area (Keith and Skjei 1974). In general, revetment facings that are highly irregular and have a shallow slope are favored biologically over structures with smooth and/or steeply sloped surfaces. Such structures tend to dissipate wave energy better and have greater ability to support various organisms (Gantt 1975).

A change in beach substrate, as a result of revetment construction, may alter the types of aquatic organisms which are able to utilize the area for growth, food, reproduction, and protection. For example, fish species requiring rocky substrates for spawning will be favored in the riprapped areas over those requiring sand, gravel, or vegetated substrates (U.S. Army Engineer District, Buffalo undated a). Heiser and Finn (1970), in a study of chum and pink salmon in marinas and bulkheaded areas in Puget Sound, found that the spaces between rocks in riprap revetted areas provided protection for salmon fry avoiding predators.

Revetments also affect the plant and animal communities in the upper foreshore and backshore zones. Revetments constructed in wetland areas can cause extensive damage to wildlife habitat. Carstea et al. (1975a) have described wetland destruction as the "most significant ecological impact of riprap construction." Revetments can damage or destroy wetlands by covering up narrow fringe marshes and altering water circulation in larger shorefront marsh areas. Wetlands are highly productive areas which filter upland runoff and function as the nutrient and sediment traps. Destruction of shorefront wetlands eliminates waterfowl feeding, resting, nesting, and nursery habitats and destroys the habitat for other birds, reptiles, and small mammals (Boberschmidt et al. 1976, Carstea et al. 1976, Herbich and Schiller 1976).

Cumulative effects. No studies were found that investigated cumulative physical and biological impacts due to the existence of a number of revetments within a coastal area. Revetments are relatively small in size. The effects of a single revetment may be relatively insignificant in a coastal area due to the size of the structure, the size of adjacent undisturbed areas, and even recruitment into the revetment-produced habitat. The physical and biological impacts from the construction of a number of revetments in a coastal area may have a synergistic effect. For example, extensive riprap revetting of a sandy coastline will change what once was a sandy habitat into a rocky intertidal habitat. Examination of the physical and biological impacts of revetment construction on a case-by-case basis ignores a host of potential cumulative physical, chemical, and biological impacts (Fetterolf 1976). No information was found regarding the cumulative effects of revetments in connection with other shoreline structures. All structures in an area should be evaluated concomitantly.

Structural and Nonstructural Alternatives

There are numerous alternative structures and materials available for building revetments. They are described earlier in this section and more completely in the Shore Protection Manual (U.S. Army Corps of Engineers 1973b) and the Survey of Coastal Revetment Types (McCartney 1976). In addition to the alternative designs and materials for revetments, either offshore breakwaters, groins, or bulkheads may constitute alternatives depending on the conditions at the site.

A revetment generally protects the landward area from erosion or scour due to waves or currents. An offshore breakwater may accomplish this same purpose by dissipating the wave energy before it strikes the eroding land area. A breakwater may secondarily interrupt the longshore littoral transport of sediments. This can buildup the beach which further protects the adjacent uplands. Objections to a breakwater as an alternative to a revetment are the cost, the interruption of longshore transport and possible impact on adjoining land areas, and the visual impact. In addition, a breakwater might constitute a hazard to navigation.

A groin or system of groins might indirectly accomplish the same function as a revetment by causing the accumulation of littoral drift which widens the beach cross section and ultimately protects uplands from wave attack. The groins, might reduce wave attack depending on spacing, height of the groins and angle of wave attack. The groins can cause undesirable side effects due to their tendency to interrupt longshore transport with the resultant impact on downdrift beaches. Erosion problems are, in some instances, only displaced by groins.

A bulkhead or seawall could be used as an alternative to a revetment. However, due to the greater expense and lack of environmental advantages, bulkheads would normally not be selected as alternatives to revetments. The circumstances under which bulkheads are used are described in another section of this report.

There are a number of nonstructural procedures which may constitute viable alternatives to the revetments depending on the site specific circumstances.

Beach nourishment from onshore or offshore locations can be used to widen and raise the beach profile. This, in turn, will dissipate the wave energy and may reduce erosion of the upland areas. This solution is temporary as the wave energy causing erosion will be focused on the new beach and, in time, transport the sand either offshore or alongshore, thus re-exposing the eroding area. Beach nourishment can also be used in conjunction with groins as an alternative to revetments.

Vegetation can also be used to retard erosion. Vegetation is particularly suitable against wind- or rain-caused erosion. Vegetation cannot withstand constant action of waves or currents and would need to be supplemented by other structures, or means, to prevent erosion. Vegetation is often used well above the surf zone for stabilization and accretion of sand on dune areas. In areas of relatively low wave energy, the establishment of a fringe marsh might be an alternative to revetment construction.

Most structures exposed to sea conditions are ultimately subject to erosion and failure. This problem can be avoided by zoning against development of foredunes, cliffs, or other areas subject to erosion by the sea. Setback regulations are another means of assuring that structures will not be threatened by shoreline erosion at a future date. One problem is that it is not always possible to forecast the extent of possible erosion over the life of the structure. This is particularly true in cases where groins, jetties, and breakwaters are being constructed in adjacent areas which might lead to rapid accretion or erosion of the shoreline. Also, unusual storm and wave conditions can have drastic effects on a shoreline that has been reasonably stable in the previous years. Assuming an upland building or facility is threatened by an eroding shoreline, an alternative to revetting the shoreline is to move the building or facility back on the lot, leaving the forward part of the land to erode. This, of course, requires sufficient land to allow relocation of the endangered building and a structure which can be economically moved. This remedial action might have to be repeated in the future.

Regional Considerations

Riprap revetments are a common means of protecting eroding shorelines in Puget Sound (Coastal Region 1). They are also common in estuaries and harbors along the coast of Washington, Oregon, and northern California. Riprap revetments are used to protect railroad tracks, roadbeds, residential lots, and uplands from erosion. Heiser and Finn (1970) studied chum and pink salmon in marinas and bulkheaded areas in Puget Sound. These authors recommended using riprap revetments with irregular, 40° or less angle facings in lieu of vertical bulkheads as this type of revetment provides protective habitat for young salmon.

No information sources concerning revetments unique to Coastal Regions 2, 6, 7, or 8 were found. Physical and biological impacts are similar to those previously described.

Limited quantitites of hard igneous rock in peninsular Florida (Coastal Regions 3, 4, and 5) make riprap revetments expensive as rock must often be shipped in from other states. Coquina rock, mined from quarries in the St. Augustine area,has proven to be a durable construction material for marine structures; however, this source of supply is almost exhausted. Limited supplies of hard native limestone are available in the Tampa area (Collier 1975).

RAMPS

Definition

A ramp is a uniformly sloping platform, walkway, or driveway. The ramp commonly seen in the coastal environment is a sloping platform for launching small craft. A launching ramp will normally slope continuously from above the high water line to below the low water line to allow launching of boats or airplanes under varying tidal or water level conditions. A launching ramp may be surrounded by additional structures, such as pilings or piers, and may be protected by a breakwater.

Structure Functions

A launching ramp provides a means to set afloat and retrieve boats which are usually mounted on rubber-tired trailers. However, airplanes also use ramps. Launching ramps will usually be accompanied by parking lots for automobiles and trailers and will be constructed in conjunction with a landing pier or other shoreline structures, such as pilings or breakwaters.

A ramp has many of the same physical characteristics as a revetment; however, its function is different. Revetments are usually installed in high energy environments, whereas ramps are installed in relatively quiescent areas.

Site Characteristics and Environmental Conditions

Ramps extend into the water, perpendicular to the shorelines and slope at an angle of 12% to 15% from the terrestrial zone to below the low intertidal zone. They are usually constructed in areas where there is fairly deep water close to shore and where there is a reasonable amount of protection from winds and waves. Ramps are often associated with marinas and would, therefore, be placed in similar environmental conditions.

Placement Constraints

Engineering. The design of a launching ramp may vary depending on expected usage and site characteristics. Figures 37 and 38 show examples of two different ramp designs. Ramps range in width from 10 ft to over 50 ft (3 to 15 m). Length may vary to over 60 ft (18 m). The slope of a ramp should be between 12% and 15%. If the ramp slope is flatter than 12%, trailer wheel hubs have to be submerged while launching. Slopes steeper than 15% can be dangerous unless the driver is very skilled (Dunham and Finn 1974).

Dunham and Finn(1974) recommend that the ramp be paved to about 5 ft (1.5 m) below extreme low water level. There should be a level shelf of loose gravel at the end of the ramp to prevent a vehicle from sliding into the water if there is a loss of traction or brakes.

The most common construction technique uses a gravel foundation covered by a layer of concrete. The thickness of these layers ranges from 3 to 6 in (8 to 15 cm). Deep, square-shouldered grooves, perpendicular to the slope, should be pressed into the concrete during construction (Dunham and Finn 1974). This not only provides greater traction, but the ramp will last longer than one with a course finish without deep grooves.

Submerged ramps, constructed of precast slabs, have provided the most satisfactory results. One construction method uses precast 6- by 12-in slabs placed 3 in (7.5 cm) apart. The gaps are filled with coarse gravel (Dunham and Finn 1974). Other methods have not proven as successful. Large concrete bricks and building blocks often dislodge if the subgrade is soft. Asphalt paving will not hold up well if used on the submerged part of the ramp, while unpaved ramps will deteriorate (Dunham and Finn 1974).

Sufficient pier space should be provided for boarding and for holding the boat while launching. Piers are usually located on both sides of the ramp. Dunham and Finn (1974) recommend that a single-lane ramp be at least 15 ft (4.6 m) wide. They suggest that on a multiple-lane ramp,raised divider strips or marked lanes are not necessary and may reduce optimum usage during peak hours.

Proper drainage should be provided for washdown facilities which are often used in saltwater areas. Oil, grease, and other pollutants may be washed off when cleaning the boat and trailer. For this reason, drains should be connected to a sewer system rather than returned into the water.

Ramps should be placed in reasonably quiet waters to minimize the number

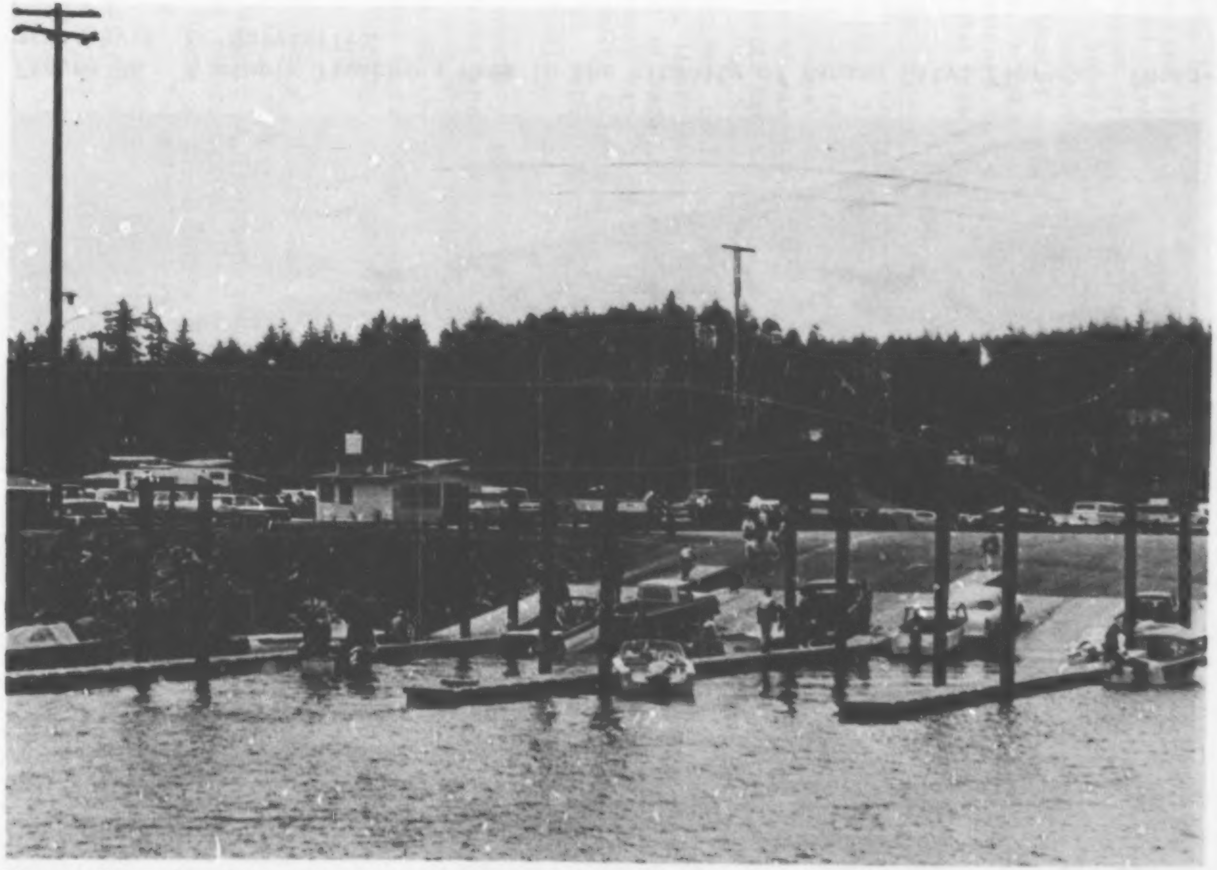


Figure 37. An elaborate launching ramp in Coos Bay, Oregon. Floating piers held in place by piles accompany the ramp. Photograph courtesy of CH_2M Hill, Inc.

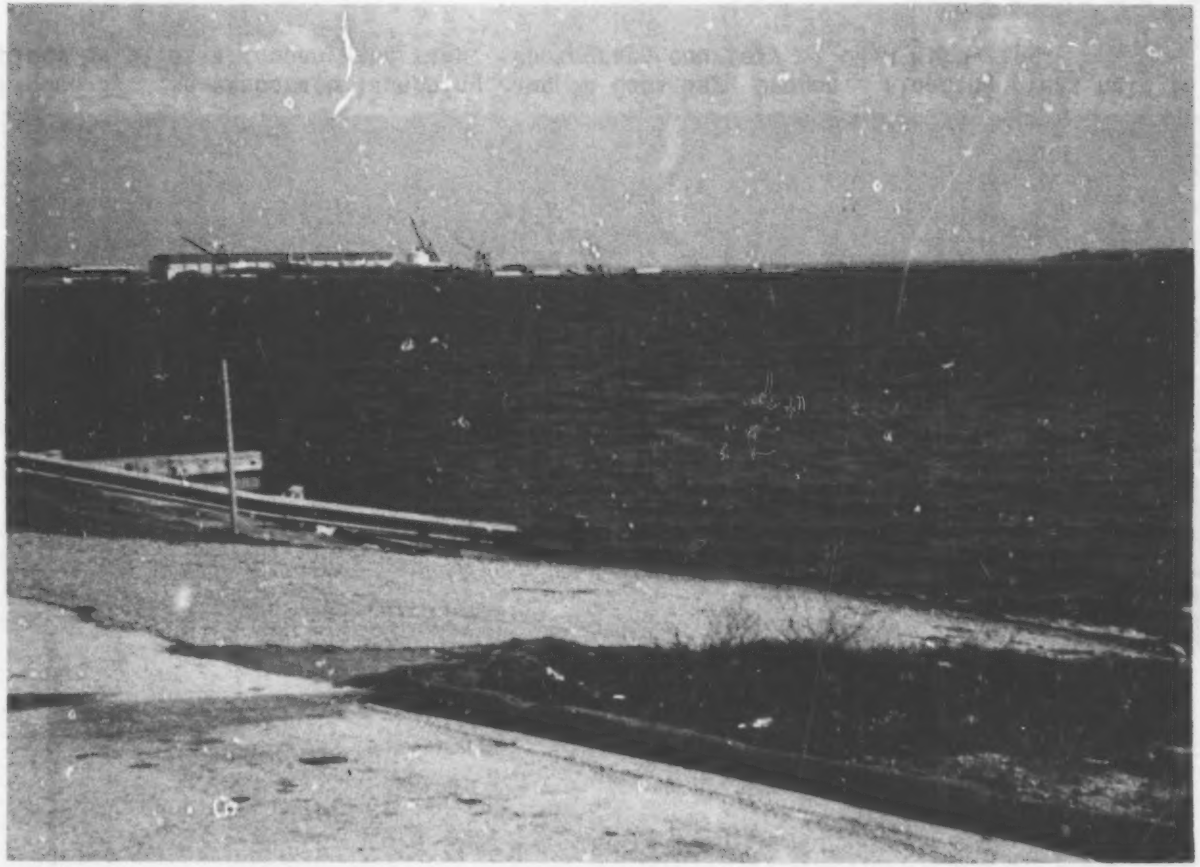


Figure 38. A simple launching ramp in the vicinity of Panama City, Florida. Photograph by E. L. Mulvihill.

of protective structures required. They should be placed in well-flushed areas to avoid the buildup of exhaust, petrochemicals, and other pollutants. To facilitate launching, it is desirable that currents be minimal. Ramps have many of the same placement constraints as solid-faced revetments. The section of this report on revetments should be reviewed before evaluating the environmental compatibility of a ramp. Structures located around the ramp, such as jetties, breakwaters and piers, should be designed to prevent adverse environmental impacts.

Socioeconomic. Community use of a ramp is encouraged over individual ownership. This will help to limit the number of ramps. One ramp usually causes minimal adverse impacts. As the number of ramps in an area increases, the impacts become more intense.

Poured concrete is probably the easiest, least costly, and most popular method of ramp construction. For the submerged ramp section, precast slab is less costly than poured concrete and provides better results (Dunham and Finn 1974).

Secondary socioimpacts should be considered when evaluating the environmental compatibility of a ramp. These include all the impacts associated with increased human usage, such as congestion, littering, and discharging pollutants.

Biological. Disturbance of wetlands should be minimized. During construction, matting or vehicles designed to prevent soil compaction should be used. Extra filling of the wetlands should be avoided. Turbidity control devices should be used when necessary to prevent adverse impacts on the local aquatic community. Ramps should be constructed in areas where minimal or no dredging is required. Review of the section on revetments in this report would help to determine the biological placement constraints for ramps.

Construction Materials

Construction materials may consist of gravel, shell, wood, concrete, steel grating, asphalt, or any other material with a reasonable degree of structural integrity and resistance to decay in an aquatic environment.

Expected Life Span

The literature did not provide the specific information on the expected life span of ramps. Unpaved or submerged asphalt ramps generally will not last as long as concrete ramps.

Summary of Physical and Biological Impacts

Construction effects. The construction of a ramp can cause suspension of sediments causing increased turbidity, reduction in productivity, smothering of benthic organisms, release of toxic substances, and altered bottom habitat. A specified area of shoreline habitat is removed from the aquatic system and is replaced, in most cases, by less productive habitat,particularly if the launching ramp area is used heavily.

The use of construction equipment will increase noise and air pollution. However, these impacts are usually slight and short in duration. Construction equipment can also disturb a wetland edge zone by causing soil compaction, which can have lasting adverse effects.

Chronic effects. The greatest impacts are usually caused by related activities, such as dredging, protective structures, channel deepening, parking facilities, and increased human usage in the area. Boats and planes cause increased turbulence as well as petrochemical and noise pollution which can affect the diversity of fish and wildlife inhabiting the area. Ramps can make formerly inaccessible areas accessible to fishermen and sightseers. This increased accessibility may result in modifications to existing populations of organisms. It is also possible that the greater frequency of boat wakes may initiate or increase shoreline erosion along the waterway, causing a need for other protective structures.

Cumulative effects. Construction of a ramp will replace some intertidal area. The associated parking facilities should be placed on the uplands. The impact of one ramp may be minimal. If the area becomes an attractive launching area, then it may attract commercial facilities. The habitat alterations increase accordingly.

Structural and Nonstructural Alternatives

The purpose of most ramps is the launching and retrieval of small craft. This same function can also be performed by a hoist which can pick the boat off a trailer and swing it into the water. Such a device usually requires a pier or other structure to allow access to water of sufficient depth. A sling would be more applicable in areas where there is relatively deep water close to shore.

A marine way (dolly) is another viable alternative which avoids the necessity of constructing a pier and/ or dredging to reach water of sufficient depth (Figure 39). This launching technique involves lifting the boat with a sling onto a platform mounted on rails (the dolly). Launching is achieved by running the boat down the railed structure and into water of sufficient depth. This technique has the advantage of allowing launching in areas with shallow slopes or at low tides. It is generally not feasible to cross extensive tidal flats with a ramp.

Regional Considerations

Most of the literature contained information applicable to all of the coastal regions. There was some information specific to the north Pacific and Gulf coast (Coastal Regions 1 and 3). In the Puget Sound area of Coastal Region 1, siting ramps on "accretional or roll-back dry beaches" should be avoided due to possible changes in beach profile (Bauer 1973). Less than 4% of the shoreline in this area consists of dry beaches. If ramps are placed in this area, the protective structures should be constructed so they do not interfere with "beach drift action." Bauer (1973) suggests considering "flexible-contour bolt and hinge segmented ramp pads that can be adapted to beach profile changes,"and also recommended that ramps be located in between "drift sectors" or "independently operating erosion-transport-accretion beach systems."

In the New Orleans District of the U.S. Army Corps of Engineers in the Coastal Region 3, the most common type of ramp consists of compacted gravel or shell covered by concrete (Carstea et al. 1976). These authors gave the dimensions of a typical boat ramp as 10 to 12 ft (3 to 4 m) wide and 40 ft (12 m) long. A typical seaplane ramp is 25 to 30 ft (8 to 9 m) wide and 55 to 60 ft (17 to 18 m) long. Concrete and timber seaplane ramps are similar to the boat ramps.

Shore profiles encountered in the various coastal regions will determine the design and feasibility of ramps and the desirability of utilizing alternate structures, such as slings and dollies.

PIERS, PILINGS AND OTHER SUPPORT STRUCTURES

Definitions

A pier is a structure, usually of open construction, extending into the water from the shore. It serves as a landing and mooring place for vessels or for recreational or commercial uses. This definition of a pier includes trestles, platforms, and docks extending into the water for similar purposes. The definition does not include bridge piers. Floating structures anchored with pilings are sometimes called floating piers. Sometimes jetties, groins, and other structures built primarily for coastal protection purposes are incorrectly called piers.

A pile is a long heavy timber, steel, or reinforced concrete post that has been driven, jacked or jetted, or cast vertically into the ground to support a load. A pile structure will normally be an open structure where water can circulate between the individual piles or pile clusters. Sheet piles are steel or concrete sheets or slabs which are driven edge to edge in a straight row to form a bulkhead or wall. They can also be driven in circles, squares, or in other closed shapes to form bridge

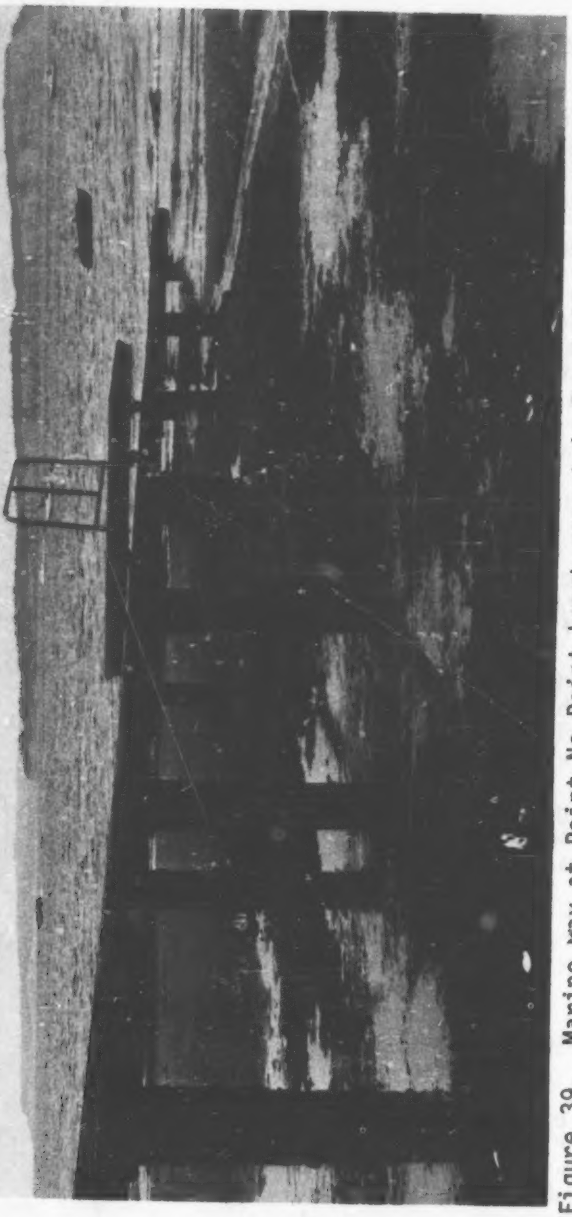


Figure 39. Marine way at Point No Point beach resort in Puget Sound, Washington. Photograph was taken at low tide. Photograph by C. A. Francisco.

piers, cofferdams, or caissons. Unlike individual piles, use of sheet piles normally will not result in an open structure.

Structure Functions

A pier usually functions as a landing and mooring place for vessels. Such a pier might also be used for loading or discharging cargo. Another function is to provide access to deep water from land. This is usually in conjunction with a landing or mooring place. A pier can also be used for boat launching and retrieval by means of a hoisting mechanism located on the pier. A pier may also provide recreational usage, as for fishing or sight-seeing. Used for these purposes, a pier might also serve as a platform for restaurants or other commercial ventures.

Separately or in clusters, pilings can perform several functions including:

- Mooring vessels, anchoring floating rafts or floating platforms (Figure 40);
- Supporting aids to navigation, such as lights, ranges, day markers, channel markers, or reflectors (Figure 41);
- Serving as the fenders or protective features for piers, landings, bridges, or other structures.

Pilings are also the basic element in many larger structures used for the mooring vessels and providing coastal protection.

Site Characteristics and Environmental Conditions

Piers extend into the water from a bulkhead or from the natural shoreline. They may extend in different directions to various depths, depending on navigational requirements or their designated function. The location of a single pile or piling is also dependent on function.

Piers, pilings, and pile-supported structures frequently occur with the marinas which are often located in estuaries and bays.

Placement Constraints

Engineering. A typical residential fixed pier is 40 to 60 ft (12 to 18 m) in length. For a marina complex it is common for a pier to extend 200 to 250 ft or 61 to 76 m (Carstea et al. 1975). Piers may be straight or have "L" or "T" configurations (Figure 42).

Piles are driven to a depth which will provide stability. This depends on the bottom characteristics of the site, as well as the lateral forces working against the structure. For example, a pier used for mooring purposes would be subjected to the forces of a vessel striking the side and would, therefore, have to support a greater lateral load than a pier used solely for fishing. The length of pile extending above the water is dependent on wave height and tide. According to Carstea et al. (1976) enough pile should be exposed to allow the decking to remain at least 3 ft (0.9 m) above the water and provide 3 to 4 ft (0.9 to 1.2 m) for mooring or handrails.

Pile dimensions vary greatly. A mooring pile is usually around 10 in (25 cm) in diameter with 8 to 10 ft (2.4 to 3.0 m) exposed above mean high water (Carstea et al. 1975a). A dolphin is usually constructed with a center pile approximately 12 to 14 in (30.5 to 35.6 cm) in diameter, surrounded with piles from 8 to 10 in (20.3 to 25.4 cm) in diameter. A heavy wire rope is generally used to bind them together (Carstea et al. 1975a).

Wood pilings should be treated to prevent decay and destruction due to marine borers (Figure 43). Treatment may include toxic surface coatings, pile sheathing, or creosote-coal tar impregnation. In areas where gribble, Limnoria, and marine clam, Pholas, attack are common, the American Wood-Preservers' Association (AWPA) C3 Standard recommends a dual treatment for wood pilings (Henry and Webb 1974). The addition of an insecticide may retard infestation (Lindgren 1974). Methods of protection are updated by the AWPA and should be consulted periodically.

An open-pile structure is recommended over a solid-fill structure. The

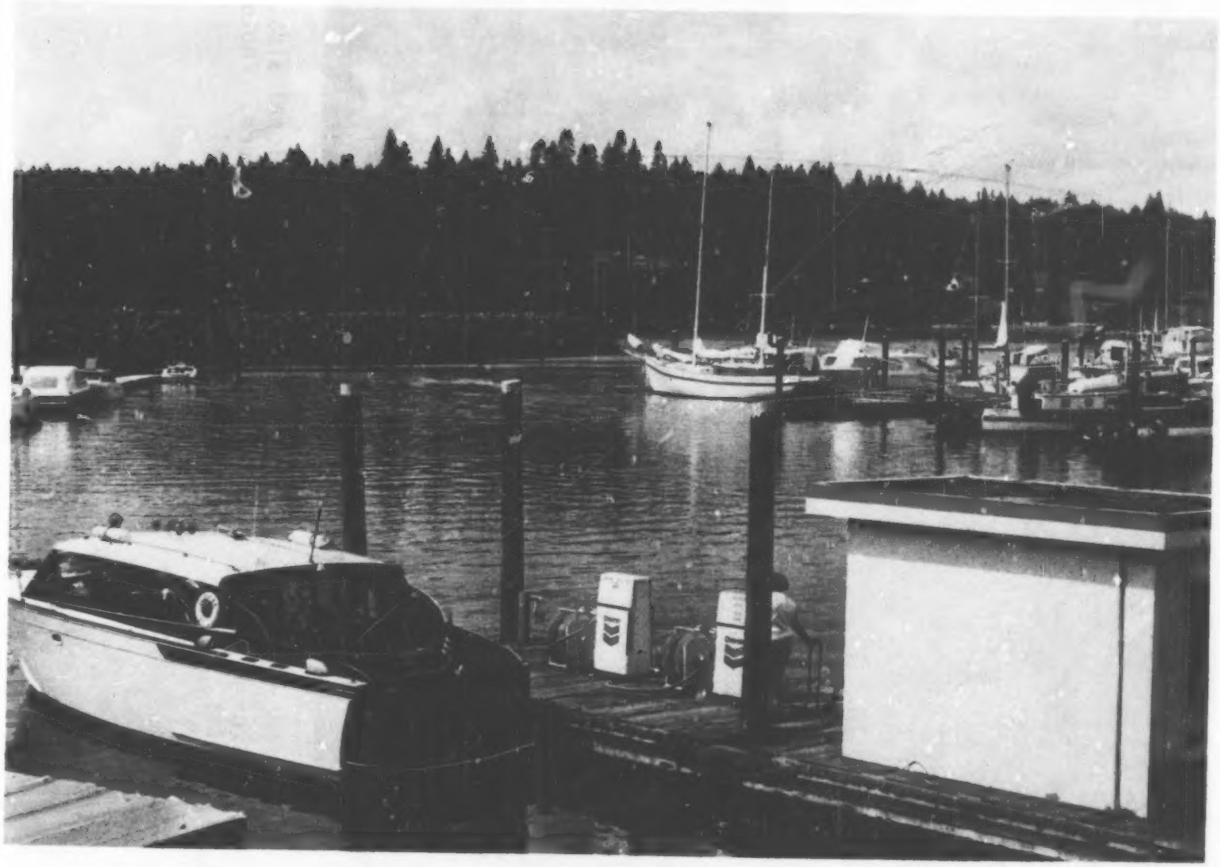


Figure 40. Floating pier at Kingston Marina, Kingston, Washington. Note rubble mound breakwater in background. Photograph by C. A. Francisco

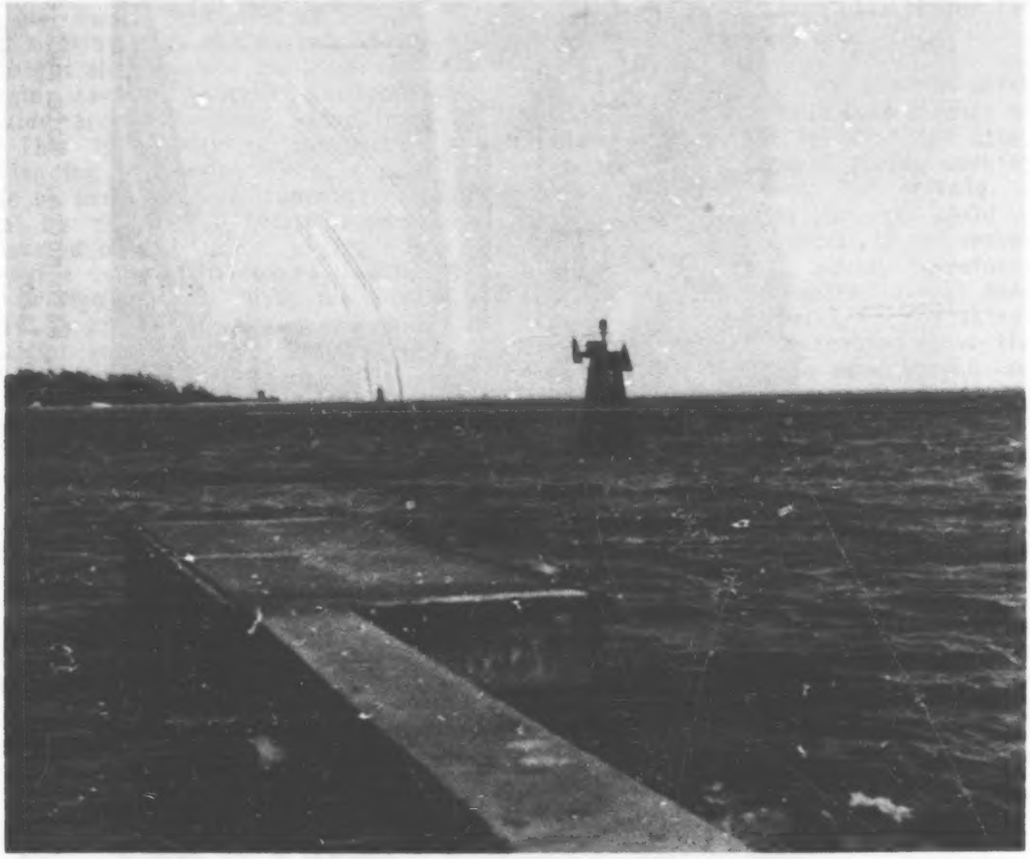


Figure 41. Piling in Key West, Florida supports navigational aids. A concrete capped pile pier is also noticeable in the picture. Photograph by E. L. Mulvihill.

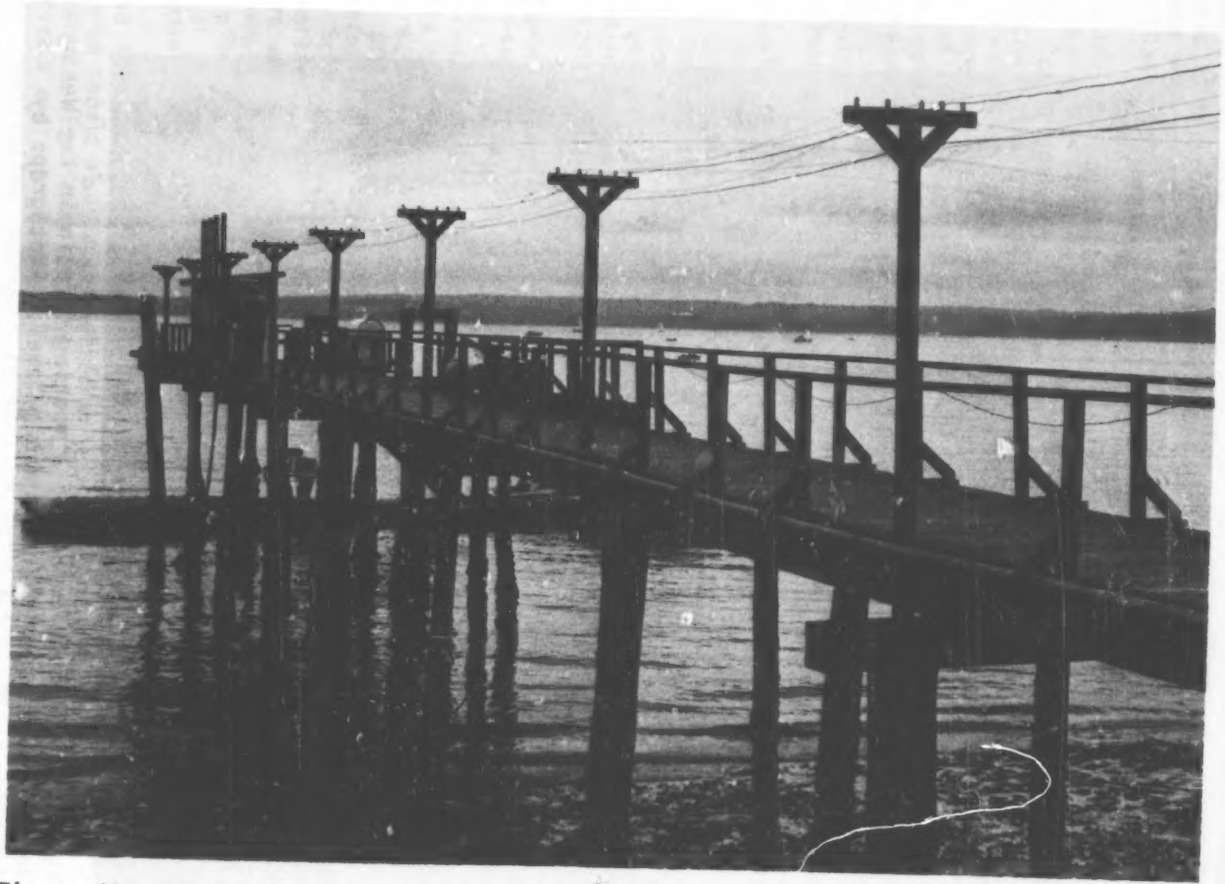


Figure 42. Open-pile pier near Hansville, Washington. Note the floating pier at the end. Photograph by C. A. Francisco.

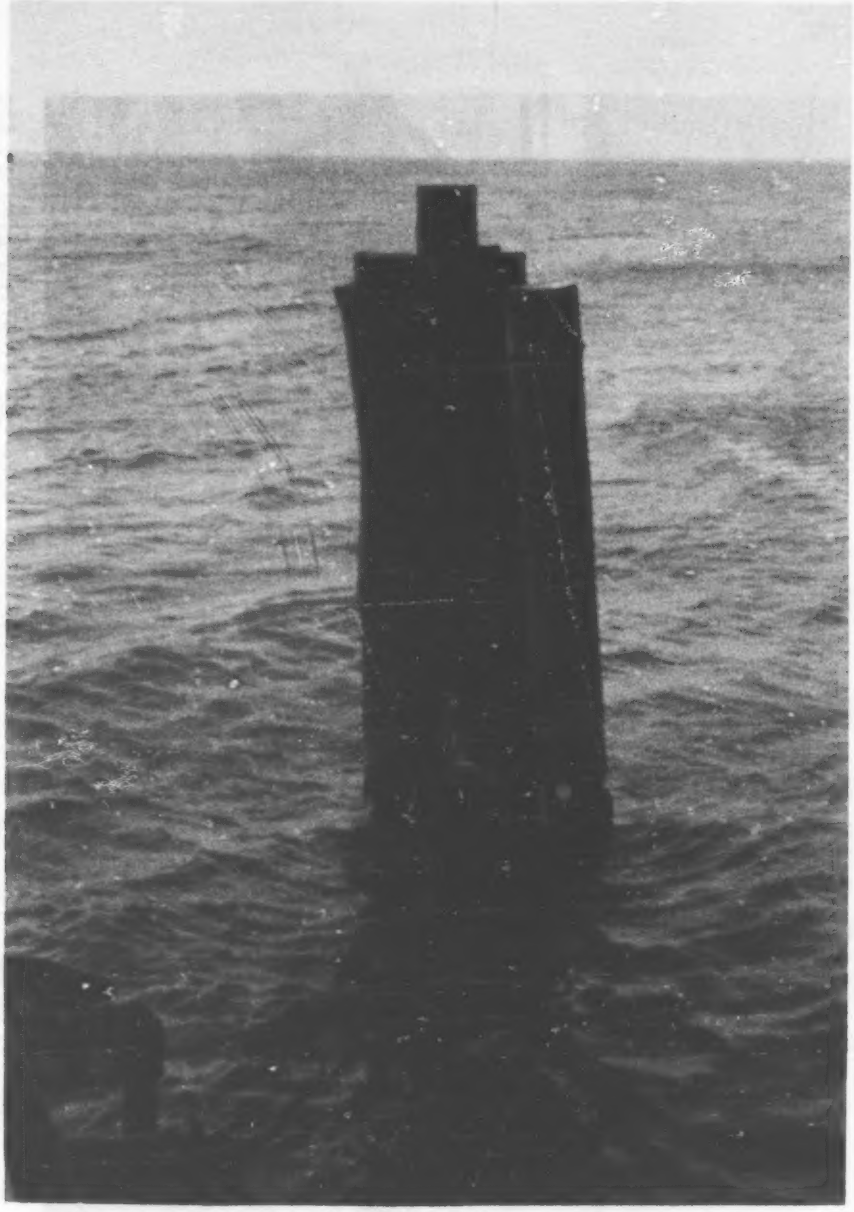


Figure 43. Gribble damage to a mooring dolphin in Key West, Florida can be seen near the water level. Photograph by E. L. Mulvihill.

advantages include fewer adverse environmental impacts and ease of removal if so desired. Open-pile structures are also advantageous where substrate conditions are unstable. Adequate spacing of piles is important to prevent interference with water and sediment movement (Bauer 1973).

Site characteristics should influence the design of a pier. According to the Coastal Plains Center for Marine Development Service (1973), floating piers can affect beach sand movement. They recommend open pile piers in the areas of significant littoral transport and longshore currents. Floating piers are suggested for areas where visual impacts should be minimized and where boat traffic would not be hindered by their presence.

Another factor to consider is tidal range. Where the tidal range is above 4 ft (1.2 m), floating piers are recommended because they provide easier access to boats throughout the tidal cycle (Ayers and Stokes 1976). Floats can be removed in the winter to avoid ice damage (Carstea et al. 1975a).

During the life span of pilings or a pile-supported structure, several changes usually occur which should be considered in the design. These changes alter the impact of forces acting on the structure. As marine growth increases on the pile, the diameter, roughness, and concomitant drag coefficient will increase. Scouring at the base of the pile will decrease pile support. Also, as piles are attacked by wood borers or as they corrode, structural damage will decrease pile strength. (See U.S. Army Corps of Engineers 1973b for further information and calculations).

The type of wave force occurring in the area should also be considered in the design. For example, breaking waves create a greater force on the pile than do nonbreaking waves. (U.S. Army Corps of Engineers 1973b should be consulted for further information and calculations.) The size, number, and placement of piling should be correlated to the various energy zones in which the pier is located.

Socioeconomic. The number and size of pile-supported structures and piers should be minimized in a given area. The use of over-water locations for non-water-dependent structures should be discouraged (Carstea et al. 1975a). To limit the number of piers, it is suggested that single piers be used cooperatively by the community. This is particularly stressed for subdivisions, motels, and multiple dwellings (South Carolina Marine Resources Division 1974). Structure size should be restricted to that which is necessary for designated purposes. Piers should not hinder public use of the water, navigation, or adjacent shoreline. Extension of the structure beyond the mean high water line should be avoided (Carstea et al. 1976). The socioeconomic impacts of public, private, or joint use of a pier should be considered.

Biological. During construction, turbidity should be kept to a minimum and turbidity control devices should be used when necessary. Alterations of shoreline and littoral habitat should be avoided (Florida Game and Freshwater Fish Commission 1975). The placement of the structure relative to the sun, as well as the height and width of the deck, are important factors to consider. The structure should be placed high enough above the water or marsh surface to prevent shading. A narrow pier extending from north to south would not produce as much shade as a wide pier running from east to west(Gifford 1977). The damage to wetlands can be minimized by constructing an elevated boardwalk to provide access to the dock or pier (Environmental Quality Laboratory Inc. 1977). The size, number, and placement of piling should be evaluated relative to the various biological zones over which the pier will extend.

Construction Materials

Piers, pilings, and structure supports are generally constructed of wood, concrete, or steel. Decking, stringers, bents, and caps are made from wood, steel, or concrete members of various sizes (Figure 44). Construction materials that do not release toxic substances are preferred.

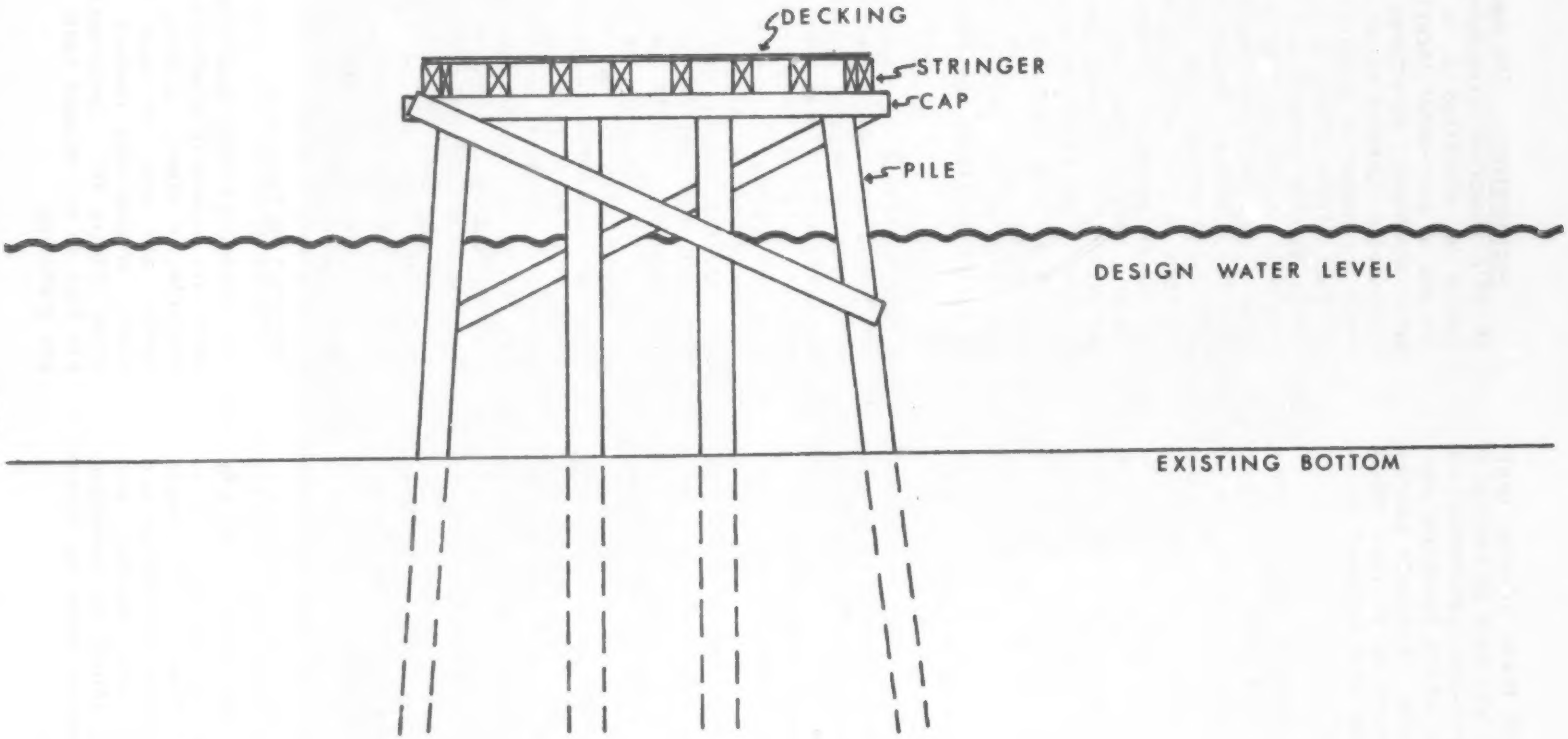

DECKING
STRINGER
CAP
PILE
DESIGN WATER LEVEL
EXISTING BOTTOM

Figure 44. Cross-sectional view of a typical pier. Dimensions and details to be determined by particular site conditions.

Water quality should be considered when choosing construction materials. Areas with poor water quality will generally not support populations of gribbles or borers. If materials that are not resistant to their attack are utilized and water quality is significantly improved, there may be problems with premature structural failure.

Expected Life Span

Pilings of wood, steel, or concrete will generally have a life expectancy of 30 yr or more if they are treated. The environmental factors of an area greatly affect deterioration rates. Conditions of high salinity and high temperature, along with the boring organisms, will likely increase the deterioration process to some degree.

Plans for removing the piling and other support structures after their effective life span should be submitted when structure is proposed for construction. There are severe navigational problems in many areas of the United States,such as in New York Harbor due to the chronic decay and drifting away of pieces of old support structures. Piles or portions of piles remaining just below the water level also present navigational hazards.

Summary of Physical and Biological Impacts

Construction effects. Construction causes increased turbidity and sedimentation which, depending on severity, may reduce primary productivity, interfere with respiration of fish, alter the suitability of spawning areas, reduce bottom habitat diversity, and smother benthic organisms(Carstea et al.1975b). Resuspended bottom sediments may release toxic substances. Noise and vibration, along with turbidity, may temporarily drive fish or invertebrates from the area or cause behavioral modifications. However, in some instances fishes have been attracted to construction sites due to the suspension of benthic organisms.

Chronic effects. Docks and piers can cause navigational problems and interfere with public use of the water. Conflicts may arise concerning adjacent land uses and area aesthetics. In areas where longshore currents, tides,and littoral transport are influential, floating piers can alter beach sand movement patterns (Coastal Plains Center for Marine Development Service 1973).

Shading from pile-supported structures may modify the water temperature and wetland habitat. Depending on the amount of shading, there may be a reduction or absence of algae and grasses under piers (Gifford 1977). But it should also be noted that piling and piers offer substrate for algae growth in some areas where algae did not formerly grow because the bottom was below the photic zone or presented unstable sediment conditions. White (1975) indicated that single residential piers in fresh water are not likely to cause a significant reduction in phytoplankton production.

Increased use of the area causes related impacts. Boat exhaust and domestic emissions can decrease water quality (Carstea et al. 1975b). Impacts may also be caused by increased fishing and litter disposal (Gifford 1977).

Unless treated, the pilings and other structures provide suitable substrate for algae and new attachment surfaces for invertebrates. These structures also provide cover and feeding sites for fishes and may be used by various birds for nesting or perching (Carstea et al. 1976). Sessile organisms on the exposed surfaces of a piling or other structure as well as the presence of the structure can attract motile organisms, such as fishes, which feed upon the organisms or use the structure for shelter. Such areas generally offer very good fishing. Piles offer resting places and feeding observation posts for coastal or marine birds, such as pelicans, kingfishers, herons, egrets, and cormorants (Carstea et al. 1976). The use of piles and piers by gulls seems to be a universal phenomenon. Channel markers are frequently used as nesting platforms by osprey.

Cumulative effects. As the number of pile supported structures increase in a given area, the impacts on that area

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will increase. The magnitude of adverse impacts may be dependent on the characteristics of the site and on the type of structures in the area. Open pile structures do not impede water or sediment movement unless the pilings are spaced very closely. Sediment deposits will build up if too many pilings are located in a poorly flushed area or in one of slow water flow. The shoreline will stop littoral drift, filling with sediment (Carstea et al. 1976).

The impact from shading increases as the area being shaded increases in size. Water temperature modifications and reduced primary productivity may have an adverse impact on the food chain. The absence of algae and grasses eliminates hiding areas for fish and other organisms, but this may be offset by the new habitat created on the submerged structures (Figure 45).

Structural and Nonstructural Alternatives

The commonly noted function of a pier is to serve as a landing place for vessels. Piers, due to their open structure, disrupt water circulation and bottom dwelling species much less than alternative solid structures, such as walls or sheet pile caissons.

The most common alternatives for piers are:

- o For mooring vessels, an anchor or mooring buoy could be used. This is more common in New England and areas of extreme tidal range.
- o For mooring vessels and providing access to the shore, a floating pier could be used. This alternative might be aesthetically more desirable but will probably cause increased shading and affect littoral transport.

If the objective is to eliminate the pier, there are two nonstructural alternatives available:

- o Combine the purpose of the proposed pier with that of piers in the vicinity to reduce the overall number of piers.
- o Use the launching ramps or other launching structures. Provide upland storage of vessels. This, of course, is limited to smaller size vessels which can be conveniently removed and transported on dry land.
- o Form community marinas to eliminate single piers at each waterfront lot.

Aside from the aesthetic considerations, loss of navigable water area, and-in rare instances-interference with sand movements, the impacts of open pier structures are minimal. Solid pier structures are generally less desirable and more costly. Elimination of piers by multiple use of existing piers or launching facilities appears to be the best alternative.

Regional Considerations

Very little information was found regarding regional specific aspects of piers, pilings, and other support structures. The types of materials utilized will vary according to availability within each region. The length of piers may vary depending on the distance to deep water which is generally quite different on the Gulf coast (Coastal Region 3) and in the Chesapeake Bay (Coastal Region 6) as compared to areas in Puget Sound (Coastal Region 1) and in New England (Coastal Region 7). The length of piles may also vary depending on the nature of sediments encountered in a region. In areas where bedrock is close to the water body floor, piles would be shorter. The length of friction-type piles will also be affected by sediment characteristics.

Infestation of piles by marine borers tends to vary geographically. Gribbles (Limnoria) breed only in temperatures above 57°F (14°C) and are prevalent in southern California (Coastal Region 2) and from the Gulf coast to the middle Atlantic (Coastal Regions 3, 4, 5, and 6) (Lindgren 1974). The abundance and growth rate of shipworms (Teredo) also varies geographically. Within a region, factors other than temperature affect marine borer populations. Heavily polluted areas may not be habitable by

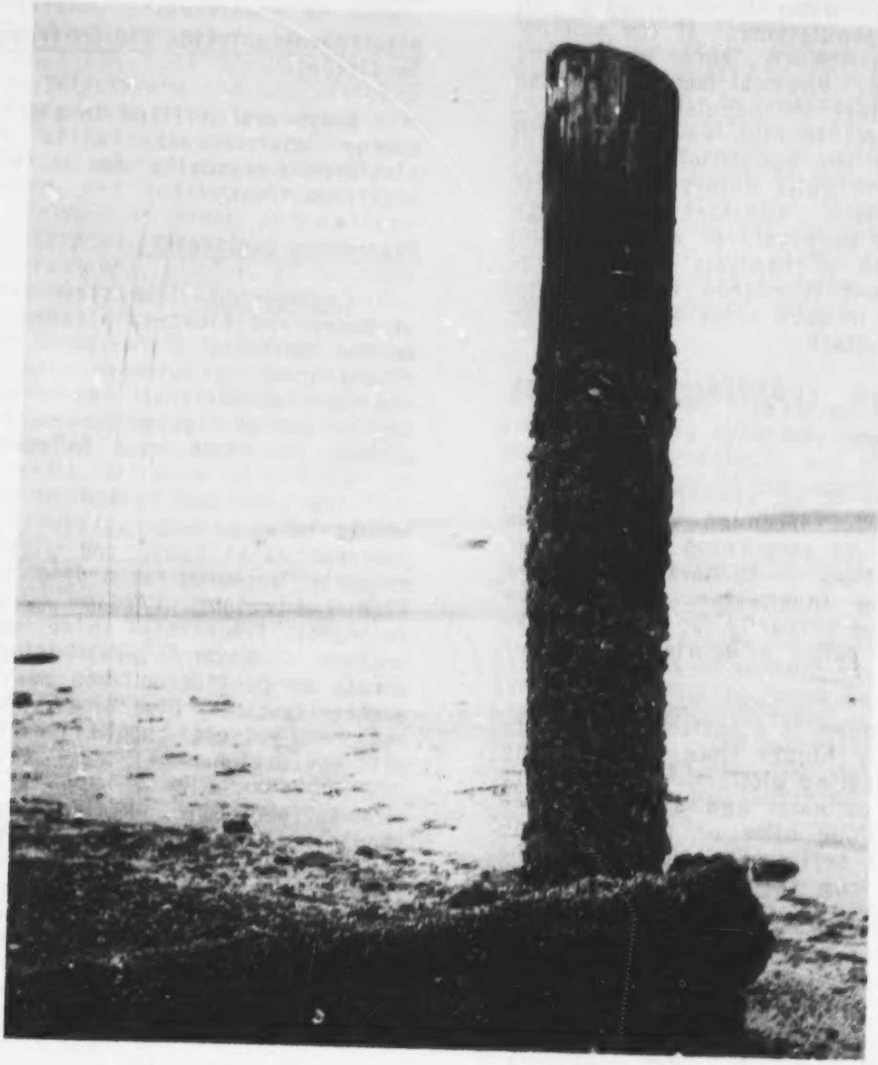

Figure 45. Submerged structures offer substrate for the attachment of various types of marine organisms. Photograph by C. A. Francisco.

borers. In such areas, pilings will not have to be replaced as frequently as in nonpolluted areas. Fluctuating quantities of fresh water in an estuary can also affect populations. If the salinity decreases sufficiently, borer populations will decrease. Physical factors may also have an effect on population density. A pile subject to high wave action will not support the population of gribbles that a pile in quiet waters will support (Hochman 1967). Constant high salinity and tropical temperatures accelerate the decomposition of chemicals used in creosote treatment (Lindgren 1974); therefore, piling in such areas are more susceptible to attack.

BUOYS AND FLOATING PLATFORMS

Definitions

A buoy is an anchored or moored floating object intended as an aid to navigation, for attachment of vessels or instrumentation, or to mark the position of something underwater. If the buoy is to be used primarily for mooring vessels, it is called a mooring or anchor buoy.

A platform is a horizontal flat surface usually higher than the adjoining area. A floating platform is a structure that floats on water and is held in place by anchors or piles or other mooring devices. A series of platforms in a line extending from the shoreline to deeper water would be considered a floating pier.

Structure Functions

Buoys are most commonly used as navigational aids to mark channels, shoals, harbor entrances, etc. Sometimes buoys have lights, reflectors, or horns mounted on them. Buoys are also used as markers for sunken objects and for suspending analytical instrumentation, such as current, wave, or water quality monitoring equipment.

Floating platforms are flat structures which are generally larger buoys or floats. They are used for recreational purposes, such as swimming and diving, or commercial purposes such as selling fishing supplies. Larger platforms used for construction or drilling would normally be considered as ships, barges, or hulls.

Site Characteristics and Environmental Conditions

Buoys are utilized in all types of energy environments, while floating platforms are usually used in relatively sheltered areas.

Placements Constraints

Engineering. The sizes and shapes of buoys and floating platforms depend on the function. For example, buoys or floats used in swimming areas or for mooring recreational craft would be smaller and of lighter construction than a buoy or float used in open water.

The site and method of placement should be considered carefully. It is important that buoys and platforms be properly anchored according to their size and weight. Areas where bottom sediments frequently shift should be avoided. Water level fluctuations should be considered when designing an anchor system. Platforms, buoys, and attached vessels should not interfere with navigation.

Socioeconomic. Platforms and buoys should not interfere with public use of the waterway. It is advisable to design them so that they are clearly visible to boaters. The presence of buoys and floats is generally accompanied by increased human usage of an area. The secondary impacts of the human usage should be considered.

Biological. If drums or barrels are utilized as floats, those once containing toxic substances are not suitable. It is advisable to coat foam floats to prevent chips and flakes from littering the water. To avoid contamination, all coatings must be dry before placing floats in the water. The submerged surfaces of buoys and floats and the anchor system offer habitat for various types of attached organisms. They also supply refuge for various types of fishes.

Construction Materials

The flotation material for floating platforms and buoys generally consists of polystyrene, ployurethane or hollow steel, aluminum, fiberglass, or concrete structures. The most popular type of floats are polystyrene and polyurethane foam. They should be coated with a preservative to prevent deterioration and attachment of marine flora and fauna. The coating may consist of polyvinylacetate emulsion or dense polyurethane (for polystyrene), fiberglass and resin (for polyurethane), plaster, or concrete (Dunham and Finn 1974). When using polyurethane, the monocellular type should be used, as it is the only type that is nonabsorbent. Extruded polystyrene (Styrofoam) is totally impermeable by water and may be preferred over expanded-pellet polystyrene (beadboard), which is more susceptible to water penetration (Dunham and Finn 1974). Polyurethane is naturally hydrocarbon-resistant. Polystyrene can be made hydrocarbon resistant. This is an important factor to consider when locating structures in an area susceptible to petroleum products. In the past, hollow floats or fiberglass or metal were used. Hollow-shell floats are more susceptible to leakage and are being replaced by shells filled with foam. Wood flotation devices are used in some areas of the country, such as the Pacific Northwest. Platform decks may be constructed from wood, concrete and plastic materials. Anchor systems may be made from rope, cable, or chain. Anchors can be patented anchors of steel or can be made of concrete blocks and various makeshift things, such as junk auto parts.

Expected Life Span

The life span of buoys and floating platforms was not addressed in the literature. Materials treated against marine growth and corrosion will last longer than untreated materials. The severity of environmental conditions where they are utilized will greatly affect their longevity.

Summary of Physical and Biological Impacts

Construction effects. The effect of the installation of buoys and floating platforms is minimal.

Chronic effects. Shaded areas caused by floating structures and the areas occupied by their anchors are usually small and generally would not be expected to result in measurable effects. Shading from platform decking may result in a small decrease in primary productivity. The impact is dependent on the size of the structure. Buoys and platforms provide habitat for sessile organisms and cover for fish. Pelagic game fish are attracted to buoys and floats. They are, therefore, popular sport fishing spots.

Cumulative effects. Cumulative effects were not considered in the literature. It is apparent, however, that there can be aesthetic and navigational problems created if the number of floating objects is allowed to proliferate.

Structural and Non-Structural Alternatives

One alternative to buoys used for navigation aids or markers would be pile structures. Mooring buoys could be replaced by fixed structures such as dolphins or piers. The necessity for buoys could be eliminated by installing a launching ramp and requiring land storage of the boats.

Regional Considerations

Most of the information in the literature is applicable to all of the coastal regions of the United States. The Buffalo District of the U.S. Army Corps of Engineers (undated a) (Coastal Region 8) proposed that general permits be issued for navigation, mooring, and special purpose buoys and floating platforms in New York State. Specific restrictions for that area included limiting a deck surface area to not more than 200 ft^2 (61 m^2) and restricting platform extension to no more than 100 ft (30.5 m) waterward from the high water line.

HARBORS FOR SMALL CRAFT

Definition

A harbor is a protected water area

offering a place of safety to vessels. Natural harbors are those where the protection is provided by the natural geography of the area. Artificial harbors are those where natural protection does not exist (i.e., on an open coast line) or where substantial structures are required to provide adequately protected water areas. Small craft harbors are protected areas whose depth and maneuvering area limit usage to small craft. Harbors specifically designed or constructed for fishing boats are included in the general definition of small craft harbors. Marina is used synonymously with small craft harbor,but generally refer to harbors for pleasure craft.

Although the word port is sometimes used interchangeably with harbor, it is clearer to use port to signify a place, usually both a harbor and town, suitable for landing people or goods.

Technically, a harbor for small craft could be the water surface in a naturally or artifically protected area in a bay, lake, or estuary. However, as commonly used in the United States, a small craft harbor also includes the necessary features for the safe navigation and mooring of small craft. This would include the following features:

o A natural or man-made entrance channel of sufficient width and depth for traffic use;

o A natural or man-made basin of sufficient depth and size for anchoring or mooring craft;

o A breakwater surrounding the basin to provide protection from natural waves and swells from passing vessels. It can also provide protection from swift currents. The breakwater might concurrently function as a jetty to assist in maintaining depth in the entrance channel or as a groin to prevent sediment or sand from entering the basin. The breakwater might incidentally serve as an access road or path to the harbor or to the waterway in which the harbor is located;

o A system of piling, floats, piers, anchor buoys, or other devices for mooring small craft.

A small craft harbor might also include the following items:

o Special facilities, such as piers for fueling and taking on provisions;

o A ramp or launching device for placing small craft in the water and removing them;

o Backup land for parking vehicles and providing access to the harbor facilities.

There is no exact definition as to how many of the above features are implied by "small craft harbor." But, many of the structures considered in this report are common components of small craft harbors (Figures 46, 47, and 48).

Small Craft Harbor Functions

The function of a small craft harbor is to provide shelter for small boats and, in some cases, to supply support facilities for the activities carried out by the boats.

Site Characteristics and Environmental Conditions

Small craft harbors usually occupy several tidal zones extending from the terrestrial zone through the subtidal zone when the accompanying parking facilities, launching ramps, and breakwaters or jetties are included.

Small craft harbors are more commonly located in bays, estuaries, inlets or coves, rather than on open coasts. Due to recent concern over construction in the intertidal and near intertidal zones and the diminishing number of feasible sites,marinas are now frequently dug out of upland areas (Carlisle 1977).

Placement Constraints

Engineering. Environmental conditions of the specific site should be

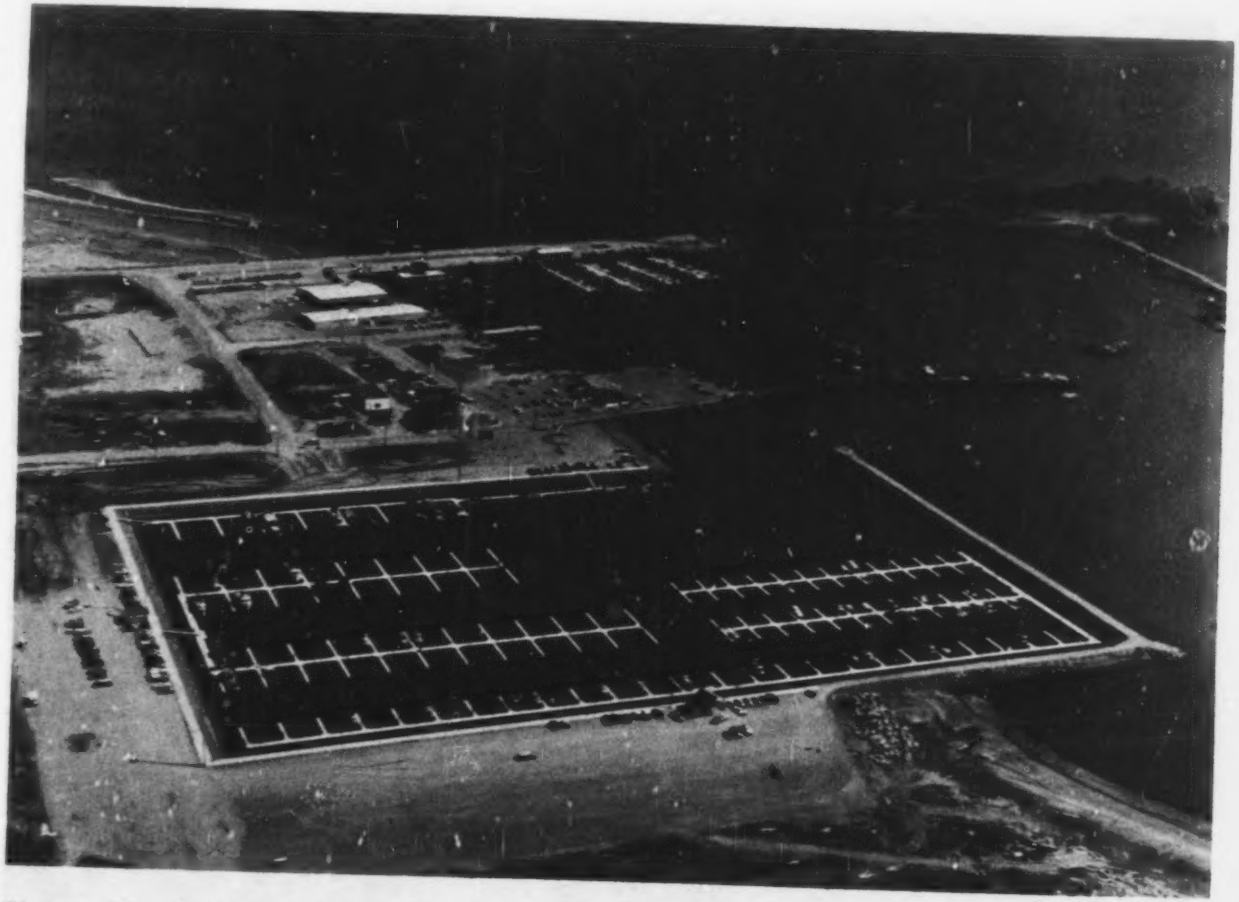

Figure 46. Crescent City, California inner boat basin. Photograph courtesy of Swan Wooster Engineering Corporation.

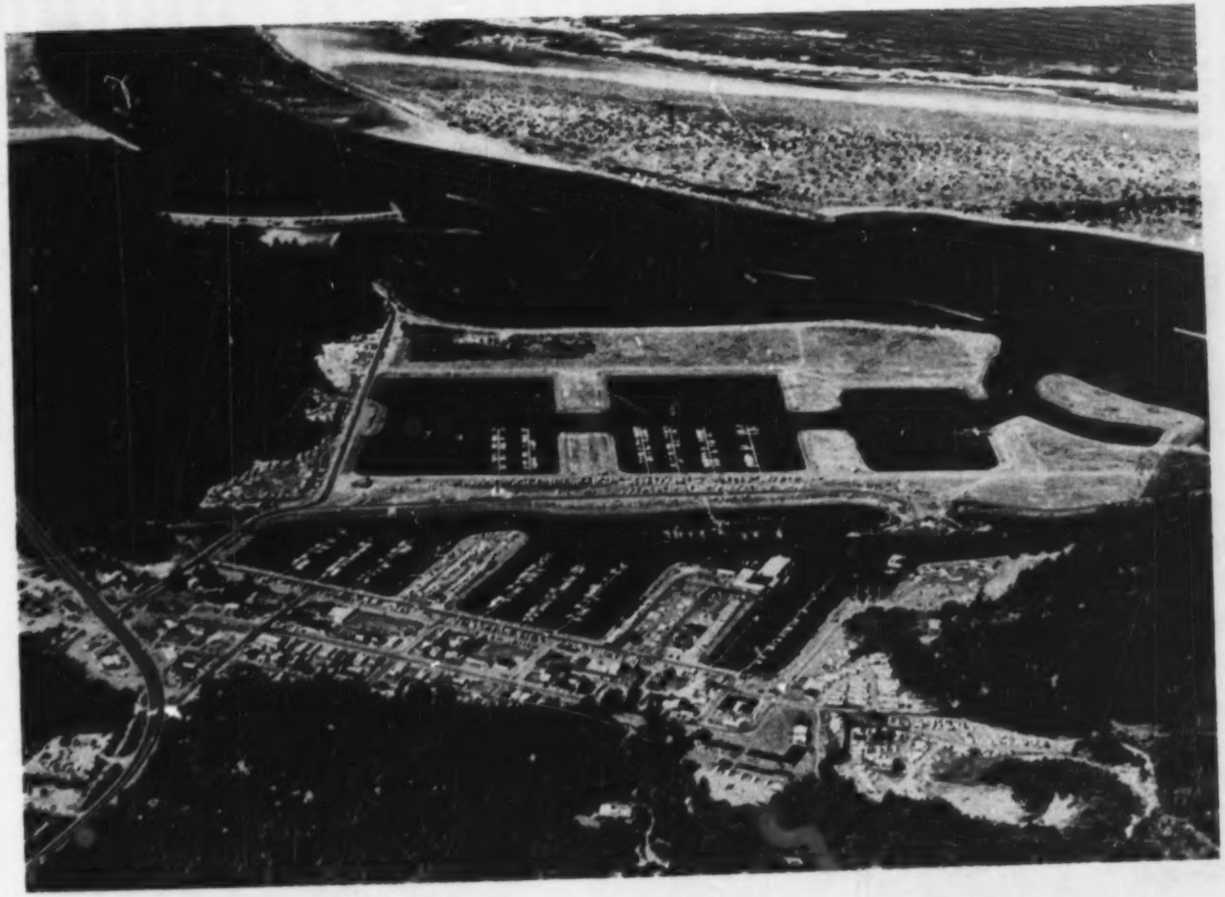

Figure 47. Winchester Bay, Oregon. Photograph courtesy of CH_2M Hill, Inc.

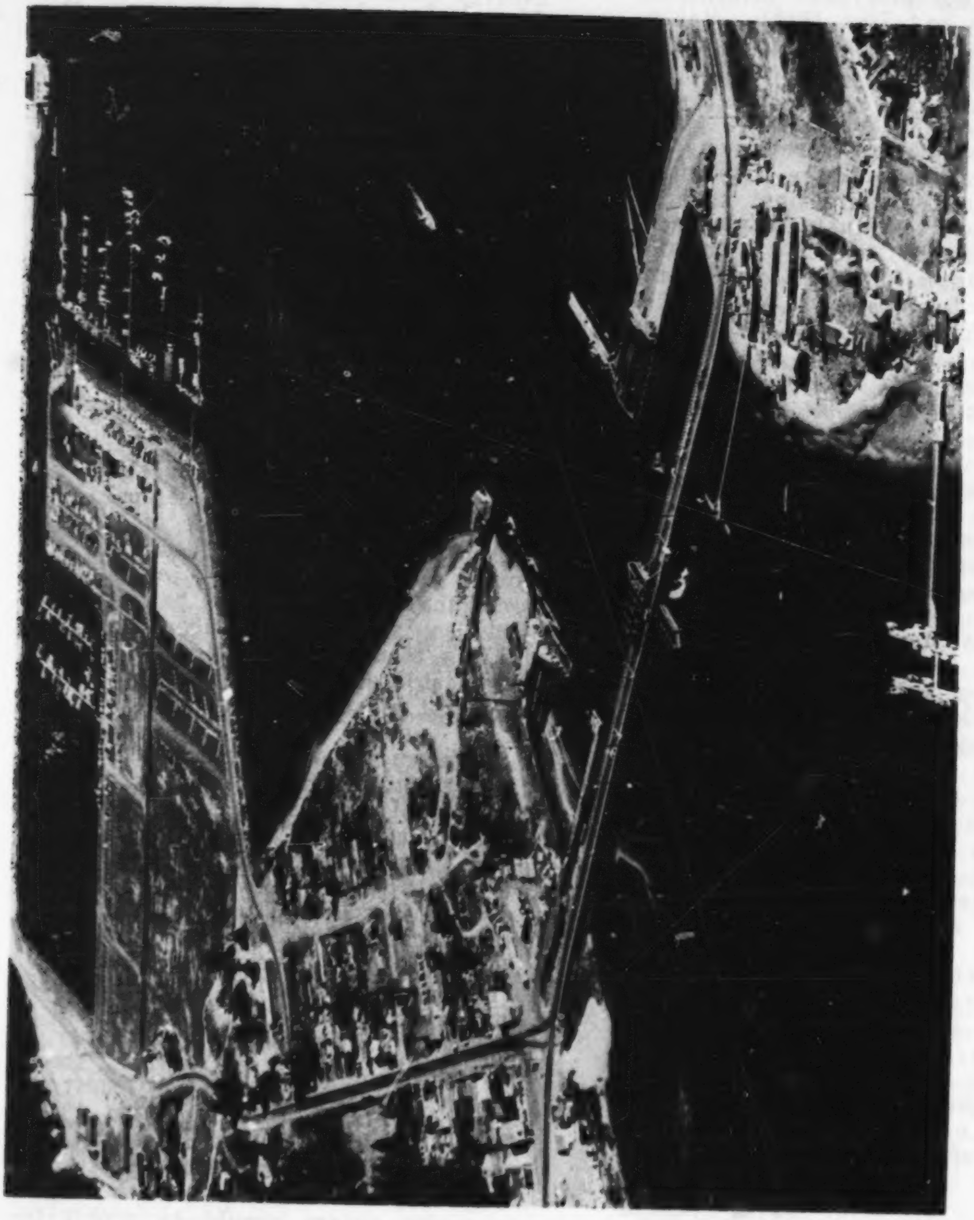

Figure 48. Charleston Harbor, Oregon. Photograph courtesy of CH_2M Hill, Inc.

considered in the design of a small craft harbor. The design should be appropriate for local weather conditions, including precipitation, wind, ice, and fog for both durability and safety reasons (Dunham and Finn 1974). Waves, shoaling, and geological factors should also be considered.

According to Clark (1974), a site with maximum natural protection will minimize alterations and the concomitant adverse impacts. Alterations, such as dredging and continual maintenance, can be avoided by selecting a location with the maximum natural physical benefits (Florida Department of Natural Resources 1973). Bauer (1973) recommends that marinas be located "...at the end of, or between drift sectors,or on self-contained pocket beaches..."to minimize impact.

A concept presented by Ketchum (1972) states that one way of reducing adverse impact on bay or inlet habitat is to construct the marina inland, connecting it to the sea by canals. This is presently being done in some areas of the United States (see Regional Considerations). Inland marinas should leave adjacent wetland communities undisturbed (Florida Game and Freshwater Fish Commission 1975). The Florida Department of Natural Resources (1973), in their list of recommendations on marina location and design, recommends that marinas catering primarily to craft smaller than 24 ft (7.3 m) should use upland dry-storage facilities, rather than occupy water space.

The entrance channel should be designed for safe navigation for vessels expected to use the harbor. Sailboats may require different design conditions from power boats. Narrow winding channels should be avoided and bends should be gradual (Dunham and Finn 1974). Traffic during busy periods should not cause excessive congestion or danger.

One of the problems consistently mentioned in the literature was that of proper water circulation and flushing within a harbor. When designing a small craft harbor, it is important that water circulation is assured. Wick (1973) suggests that the shape of a boat basin should fit water flow patterns of the area. This means avoiding square-shaped basins that create deadwater areas. Deadend canals or basins are not advised. Basins should not be deeper than the access channel (Florida Game and Freshwater Fish Commission 1975). Heiser and Finn (1970) recommend the "flow-through designs" and cite Shilshole Marina as a good example (Figure 6).They also suggest reducing stagnation by facing the entrance away from prevailing summer winds. According to Stockley (1974), open pile and floating breakwaters allow the most water circulation in a marina. Proper circulation would mean the marina should be designed in length, width, and depth so that a large percentage of the water can be exchanged each tidal cycle. Stagnant areas where exchange will not occur should be avoided. Culverts have been used in harbor construction to enhance circulation. If proper circulation is not designed into the marina, then some type of flushing mechanism should be provided. If dissolved oxygen levels become too low, mechanical aeration may be necessary (Environmental Quality Laboratory, Inc. 1977) although it is expensive and not as reliable as avoiding the situation in the first place.

Several sources recommend alternatives to bulkheading in marinas. According to Carlisle (1977), rock breakwaters with moorage along the piers in deeper water are preferable to bulkheaded areas. Slawson (1977) suggests that mooring piers be run into the water from riprap edges rather than using bulkheads at the water's edge. The section on bulkheads should be consulted for further information. With increased use of the harbor area, water quality may be threatened. Small craft harbors should not be located near sewage or industrial waste outlets (Heiser and Finn 1970). Proper disposal of litter, sewage, and runoff should be provided. Discarding scrapfish, unused bait, and fish remains in marina waters should be prohibited (Heiser and Finn 1970). Regulations limiting the amount of toxic materials that can enter the water from boats or marine structures should be enforced. Fuel should be stored and handled carefully to prevent spillage. Methods for cleaning up accidental spills should be provided (Coastal Plains Center for Marine Development Service 1973).

Socioeconomic. Small craft harbors can be more economically placed in the areas of low wave energy requiring fewer protective structures (Bauer 1973). This type of environment, which includes estuaries, bays, and marshes, is also highly productive for natural resources. Therefore, the economic and biological costs and benefits must be weighed when siting a marina.

Biological. During construction and operation of a marina, any unnecessary disturbance of adjacent areas should be avoided. Wetland and marsh habitat should be protected. Turbidity control devices should be used when necessary. Vehicles designed to minimize soil compaction should be used when working in wetlands. Shellfish beds are mentioned often as a particular area of concern (Coastal Plains Center for Marine Development Service 1973, Florida Department of Natural Resources 1973, Snow 1973). Shoreline vegetation should be left in place and used to aid in shoreline stabilization (Florida Bureau of Environmental Protection 1975). Wetland areas should be avoided as sites for fill and surfacing (Clark 1974).

Giannio and Wang(1974) recommend using dredge spoils from the marshes to establish new marshes elsewhere. Efforts should be made to create new habitats if possible. For example, riprap is recommended over bulkheading because it provides better habitat for sessile organisms. Biological impacts due to the various structures contained in small boat harbors should be considered in the total harbor evaluation. (Refer to the sections on Breakwaters, Piles and Piers, Buoys, Floating Platforms, Ramps, Groins, Jetties, Bulkheads and Revetments.)

Construction Materials

Harbors may contain one or more of the various small structures discussed in other sections of this report. The other sections should be consulted for a discussion on the various types of construction materials used in harbors.

Expected Life Span

The expected life span of a small boat harbor was not discussed in the literature. The life span of a harbor is dependent on the durability of the various structures that make up the harbor, particularly breakwaters or jetties which protect the entrance channel and basin. Specific sections of this report dealing with breakwaters and jetties should be consulted.

Summary of Physical and Biological Impacts

Construction effects. Numerous activities can be involved in harbor construction depending on the features of the harbor. One should consult the appropriate section of this report for information pertaining to the impacts of a specific structure. Major considerations are turbidity and the release of trapped toxicants from sediments.

Chronic effects. The impacts of a small craft harbor are dependent on site characteristics, the design of the harbor, and the extent of alterations that were made on the environment (Clark 1974). Carlisle (1977) states that there is generally no normal benthic succession, poor substrate, and poor water quality in harbors. Ross (1977), on the other hand, maintains that marinas do not necessarily produce poor water circulation and anoxic conditions. Although opinions varied in the literature, water quality should be considered during harbor design.

The function of a small craft harbor dictates the need for calm water which can lead to stagnation and concomitant water quality problems. Dead end canals or basins with inadequate flushing create stagnant water. This stagnant water can experience larger temperature and salinity changes than adjacent areas. Wick (1973) states that the "square-shaped boat basins require dredging and filling, and create dead water areas - all adversely affecting the natural flow system." Poor circulation of the water can lead to a buildup of organic sediments and depletion of dissolved oxygen.

Reish (1963), in his studies of Alamitos Bay Marina, discovered a drop in the benthic population in the basin area approximately one year after construction. No significant drop occurred in the channel area. Reish (1963) suggested that the decrease in the population was a result of limited water circulation. In this case the dissolved oxygen content decreased and the gray odorless substrate became black and had a strong sulfide odor. Carlisle (1977) explains a problem where harbors act as water traps creating conditions suitable for dinoflagellate blooms. These blooms die off,causing a decrease in the dissolved oxygen levels resulting in massive fish kills which in turn perpetuate the lack of oxygen.

Water quality in a harbor is further affected by boating activities. Petroleum products are released into the water from boats and trailers. The clarity of the water is influenced by boat traffic to varying degrees, depending on the depth of the water (Bowerman and Chen 1971). A study of Marina Del Ray by Bowerman and Chen (1971)showed that the shallower basins were generally not as clear as the deeper mid-channel water. The increased cloudiness can reduce light penetration, resulting in reduced photosynthesis and oxygen production.

General increased usage can cause adverse effects in the area. Potential pollution problems exist from oil spills, sewage disposal, land runoff, and erosion (U.S. Department of Commerce 1976). Copper contamination can result from protective paints on boats, floats, and other marina structures or by the treatment of hulls with copper-based toxicants. These factors, in addition to a lack of water circulation, can create serious water quality problems. According to Clark (1974) the aquatic biota is endangered by the inability of harbor waters to rid themselves of the "marina-source contaminants." Noise and air pollution may also disturb the aquatic and terrestrial inhabitants of the area.

There is some question on the advantages and disadvantages of small craft harbors in relation to fish. Where harbors cause migrating fry to move into deep water, predation is increased (Rickey 1971). The loss of shallow water areas for spawning and for nursery areas is of concern. However, according to Stephens (1977) harbors produce a "modified bay-like environment" conducive to fish habitation. The breakwaters, groins, jetties, and riprap are all considered to provide increased habitat for fish or for the organisms on which they feed. Another possible advantage is that harbor waters tend to be warmer and may be preferred by the juvenile fish (Stephens 1977). Heiser and Finn (1970) observed that pink and chum salmon fry concentrated inside marinas. They also noted that the fry were more adaptable to this type of environment and more resistant to predation than was previously thought. Rather than schooling and moving to shallower water when disturbed in undeveloped beach areas, the fry were observed to dive 3 to 5 ft (0.9 to 1.5 m) and swim away. When the fish moved into deeper water to swim around breakwaters or bulkheads, predation was increased. However, Heiser and Finn (1970) state that predation may have been less within the marina than in smaller natural beach areas due to the increased "activities which tended to discourage birds and larger fish species from attacking the salmon juveniles."

Cumulative effects. Cumulative effects of small craft harbors constructed in wetland areas may include the elimination of such areas as productive habitats. The impact on the environment increases as the area covered by these facilities increases. Decreased water quality and increased human activity over a large area is not conducive to natural productivity.

Structural and Nonstructural Alternatives

Structural alternatives to the small craft harbor can best be understood by evaluating the individual components making up the harbor. A harbor can consist of breakwaters, bulkheads, piers, ramps, revetments, and other structures, and each of these components has potential alternatives described elsewhere in this report. There are, however, alternatives to the entire harbor which are described below.

One alternative to the harbor is the upland storage of small craft. This can either be accomplished by the individual owner retaining possession of the craft or a central storage facility being constructed. Such a facility would normally be near a launching point. A means of launching is required before upland storage is a viable alternative. A ramp for use by trailer mounted craft is most commonly used,but a crane system mounted on a pier is also feasible. The main constraint of upland storage is that it is time consuming. It is also quite expensive to launch larger vessels. Upland storage is generally an alternative for small craft which trailer easily.

Alternatives for the larger vessels are individual piers or mooring buoys located in protected areas. Generally, a single well-placed boat harbor would be a preferable alternative to a proliferation of single moorages, but such a decision can only be made after a site examination.

Placement of small craft harbors inland of wetlands and tidal zones, with access by a dredged channel, may present a desirable alternative as far as location is concerned. Again, all biological, economic, and navigation factors must be weighed to make such a determination.

Regional Considerations

Most of the information in the literature can be applied to all the coastal regions. There are some considerations, however, that were mentioned in reference to particular coastal regions. The effect of small craft harbors on salmon migration was studied in the north Pacific (Coastal Region 1). This information may also be applicable to the Great Lakes (Coastal Region 8) where salmon have been introduced. Salmon fry will not go through culverts, so it is recommended that gaps be provided in breakwaters or other structures to allow the passage of salmon fry to all tidal levels without forcing the fry to enter water over 1 ft (0.3 m) deep where predation may be increased (Heiser and Finn 1970).

Only 10% of California coastal wetlands (Coastal Regions 1 and 2) remain and much of the loss is attributed to marinas (Slawson 1977). California laws can prevent most wetland development, so marinas are now being built on uplands with canals leading to the open water (Carlisle 1977).

There have been heavily contested proceedings over the construction of marinas and marina/residential developments in Florida (Coastal Regions 3, 4, and 5).

BRIDGES AND CAUSEWAYS

Definition

A bridge is a structure erected to span natural or artificial obstacles, such as rivers, highways, or railroads. A bridge supports a footpath or roadway for pedestrian, highway, or railroad traffic (Figure 49). A bridge normally is built from steel, concrete, or wood. Bridges are supported by piers and abutments. A bridge pier is a support structure in the water and should not be confused with other marine structures of the same name which serve as a landing place for boats. An abutment is the structure supporting the bridge at the point where the land meets the water as distinguished from a pier which is wholly in the water.

A causeway is a way of access, or raised road, typically across marshland or water (Figure 50). A causeway normally consists of a continuous solid fill embankment constructed of earth, sand, or rock dredged or dumped in the water or on marshy land with a roadway or pathway on it. A causeway can have culverts on open channels to allow circulation and equalization of the water heights on both sides of the structure.

Structure Functions

The basic function of both bridges and causeways is to support some form of land transportation, such as foot traffic, highway, or railroad tracks. Where the obstacle to be crossed is water or marshy land, either structure can perform the function satisfactorily. The

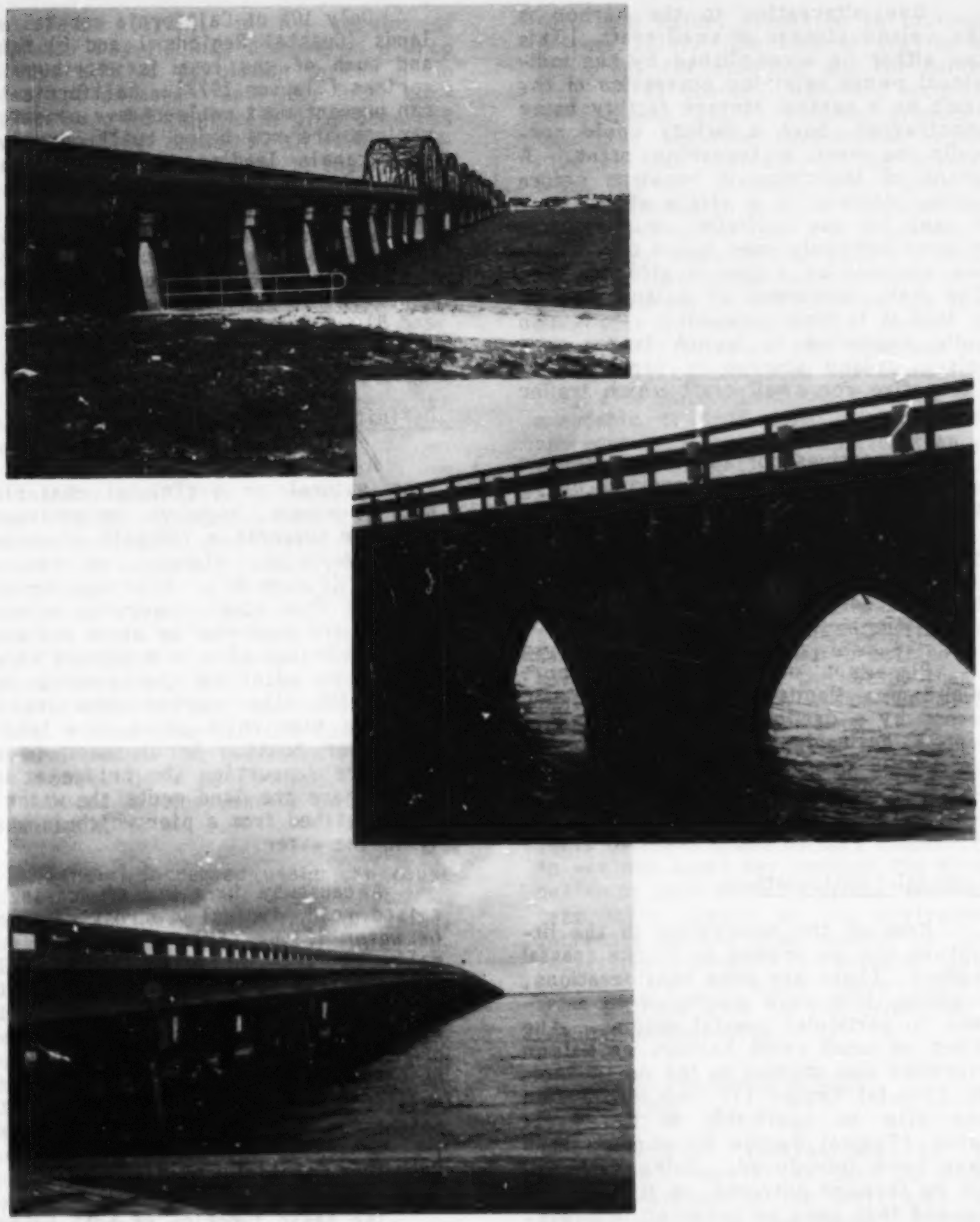

Figure 49. Many of the older bridges (top, center) along the Overseas Highway to Key West, Florida, are being replaced by new structures (bottom). Photographs by E. L. Mulvihill.

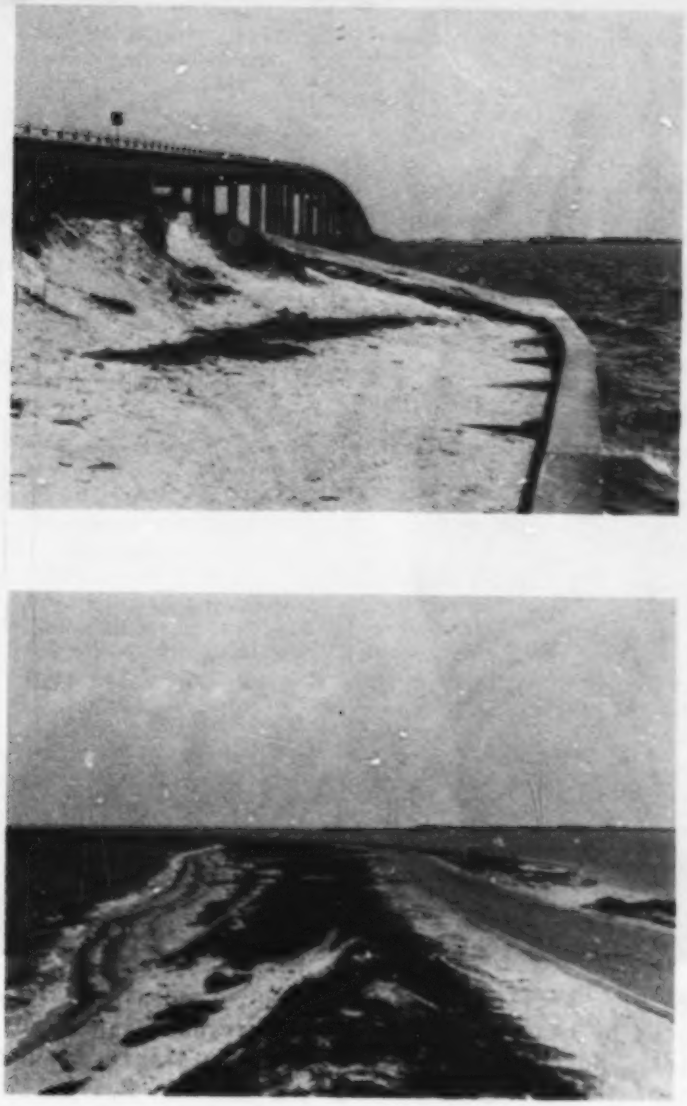

Figure 50. A bridge and causeway system crosses Apalachicola Bay on the Gulf coast of Florida. Photographs by E. L. Mulvihill.

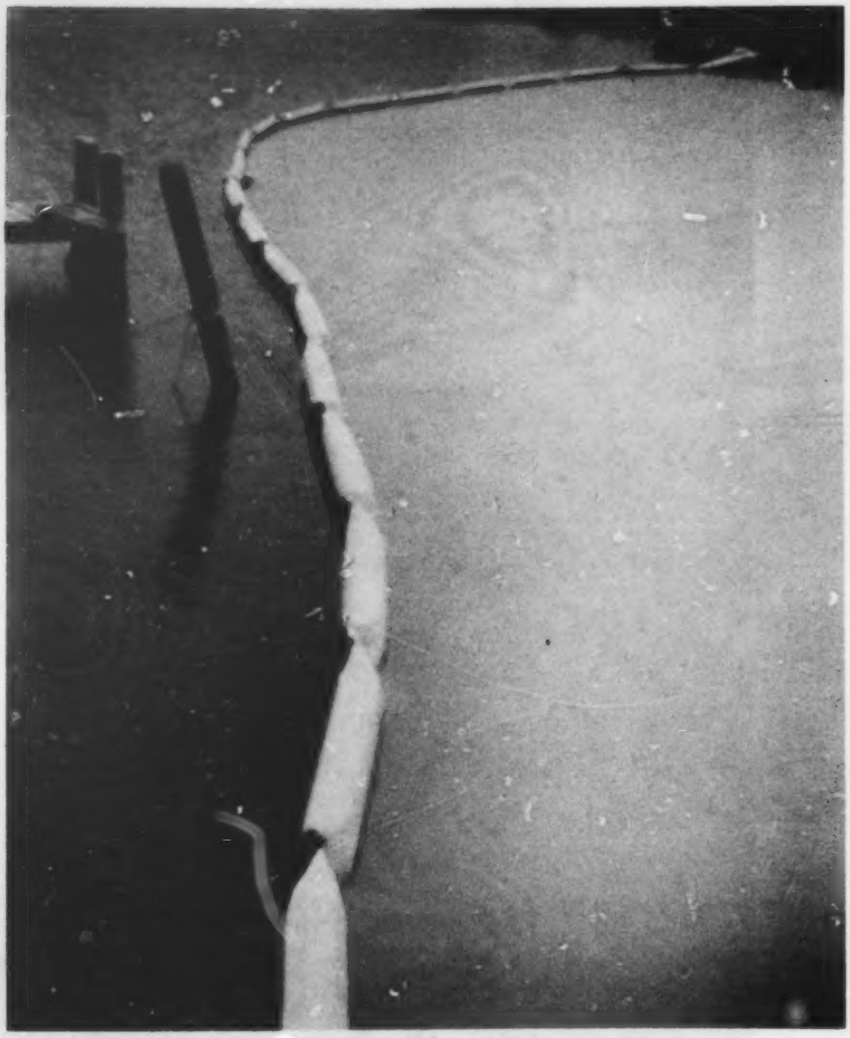

Figure 51. A silt curtain is used to contain sediment produced by causeway work on the Overseas Highway in Florida. Note the difference in water clarity on both sides of the curtain. Photograph by E. L. Mulvihill.

choice between the two will usually be based on economic, environmental, or hydraulic factors. In general, bridges will be used where there is deeper water to cross, or where navigation or water passage and circulation must be maintained. Causeways will usually be economically attractive across marshy land or the shallow water portions of estuaries.

Causeways can be used in conjunction with bridges. For instance, a causeway can be used in the shallow portion of a waterway and a bridge in the deeper portion where a causeway would be uneconomical or cause unacceptable side effects to navigation or water circulation.

Site Characteristics and Environmental Conditions

The environmental conditions in which bridges and causeways are constructed are variable. The literature referred to structures constructed across marshes, tideflats, estuaries, and channels; but construction is not limited to these locations. Bridges and causeways extend from one shoreline to another over the terrestrial zone, through the tidal or subtidal zone, and back to the terrestrial zone.

Placement Constraints

Engineering. Bridges and causeways should be designed to minimize changes in water circulation and flow. Piers or pile support structures are recommended over solid fill. Clear spans are recommended over piers, if possible (Clark 1974). The inclined approaches should also be supported by piles as opposed to fill to allow for "high-stage water passage" (Bauer 1973) or high water caused by storms. Bridge piers should be as streamlined as possible and piles should be adequately spaced to minimize the interference with water flow. According to Clark (1974), it may be necessary to enlarge the watercourse area to maintain the original cross sectional area. Bauer (1973) recommends locating bridges across straight channels rather than across meandering or shifting channel systems to avoid interference with the dynamics of such a system.

Where fill is used for support, the ditches constructed through the causeway may be an effective means to facilitate tidal inundation. However, the movement of water into and out of the wetlands behind the causeway may be altered as compared to natural conditions due to a loss of hydraulic drag. This condition has probably occurred in the Florida Everglades due to channelization of wetland areas (Davis 1977). Clewell et al. (1976) suggest considering the use of many small culverts as opposed to ditching to achieve natural flooding and drainage of a marsh area. Ditching will generally cause faster drainage of the marsh than would occur under natural circumstances.

Socioeconomic. According to Gosselink et al. (undated), bridges through marsh areas are more expensive than causeways. They stated that the cost of constructing a bridge is about four times that of constructing filled highways. When the estimated value of marsh destruction is added to the cost of a causeway, they become one-half to three-fourths as costly as bridges. However, in view of hydrologic considerations, more extensive use of bridges may be justified (Gosselink et al. undated). Both bridges and causeways may have a significant aesthetic impact on the coastal environment. Bridges and causeways are the major access modes from mainland areas to barrier islands and beaches which are utilized heavily for recreation.

Biological. When designing a roadway, wetland areas should be avoided whenever possible. Existing dikes and levees should be used if feasible. If wetlands cannot be avoided, than care must be taken to minimize biological impact. According to Gosselink et al. (undated),bridges cause less marsh destruction than causeways because bridges have less effect on water circulation. Steeper causeway and bridge approach slopes might also aid in reducing habitat destruction (Bailey 1977).

Environmental disturbances should be minimized during construction. Matting and/or vehicles designed to prevent soil compaction are recommended for use in wetlands. The turbidity control devices should be used if construction is expected to result in the significant increases in turbidity (Figure 51). Construction roads should be designed to cause the minimal adverse effects and should be removed when construction is finished. The bottom grade should be restored to what it was before alteration (Florida Game and Fresh Water Fish Commission 1975). Dredging and filling should be kept minimal. Clark (1974) advises segmental construction to avoid dredging for access. Gosselink et al. (undated) also recommend against access canals. When solid fill causeways are constructed, Gosselink et al. (undated) recommended side casting to reduce water quality degradation, long-term environmental damage, adverse aesthetic impacts, and the time required for revegetation. If hydraulic dredges are used they recommend disposal in diked waste areas to facilitate settling of suspended materials.

Construction Materials

Construction materials for bridges include steel, concrete, or wood. A causeway embankment may be constructed from soil, sand, or rock.

Expected Life Span

Information was not found in the literature about the expected life span of bridges and causeways. Both of these structures should be considered as extremely long lived and essentially a permanent change to existing conditions.

Summary of Physical and Biological Impacts

Construction effects. Construction activities are likely to cause increased turbidity and sedimentation, particularly when excavation and spoil disposal are involved. Spoil disposal may cause habitat loss, change in species composition, and water quality deterioration (Gosselink et al. undated). Revegetation is almost impossible where sandy spoil is deposited and is slow and variable when spoil is taken from brackish or saline marshes (Gosselink et al. undated).

Many aquatic and terrestrial sediments are spongy and are subject to shifting due to stress. The potential exists for shifting of sediments due to the weight of materials deposited during causeway construction. In some cases, a mud wave had been created which advanced ahead of the causeway construction.

Chronic effects. The most prominent chronic effects of bridges and causeways mentioned in the literature are an alteration in current, velocity, and water circulation patterns resulting from decreased cross sectional area. Salinity may be affected in estuarine environments and other areas subject to tidal flow. Marsh circulation may also be affected. Concomitant alterations in the flora and fauna will be dependent on the degree of salinity change. Scour pits and deposition behind abutments may result where current velocity is increased by bridge piers and approaches (McAllister 1977). Blocking of longshore currents and sedimentation may result from causeways. This is shown dramatically in Figure 52 where the silt laden water of the Fraser River is directed offshore by the deadend Roberts Bank Causeway in British Columbia. An atypical unturbid environment results between the Roberts Bank Causeway and the more southerly Tsawwassen Ferry Terminal. This can be highly detrimental to filter feeding benthos (Rounsefell 1972). Impoundment of water upstream from a causeway can adversely affect marsh vegetation, reducing the amount of plant biomass for the food webs and decreasing the value of the marsh as wildlife habitat (Sipple 1974a). The impoundment of water above a causeway can lead to secondary environmental alterations, such as stream channelization to prevent flooding. A study of the causeway in the Strait of Canso, Nova Scotia, revealed that the once dominating tidal currents were superseded by wind driven currents as a result of the causeway. The currents were not only slower, but also more variable. Salinity and temperature stratification were also altered (Vilks et al. 1975).

The weight of material used for causeway fill can cause changes in the elevation in adjoining areas. Marshlands are especially vulnerable to these types of changes due to their relatively spongy composition. Most wetland plants are very sensitive to changes in their

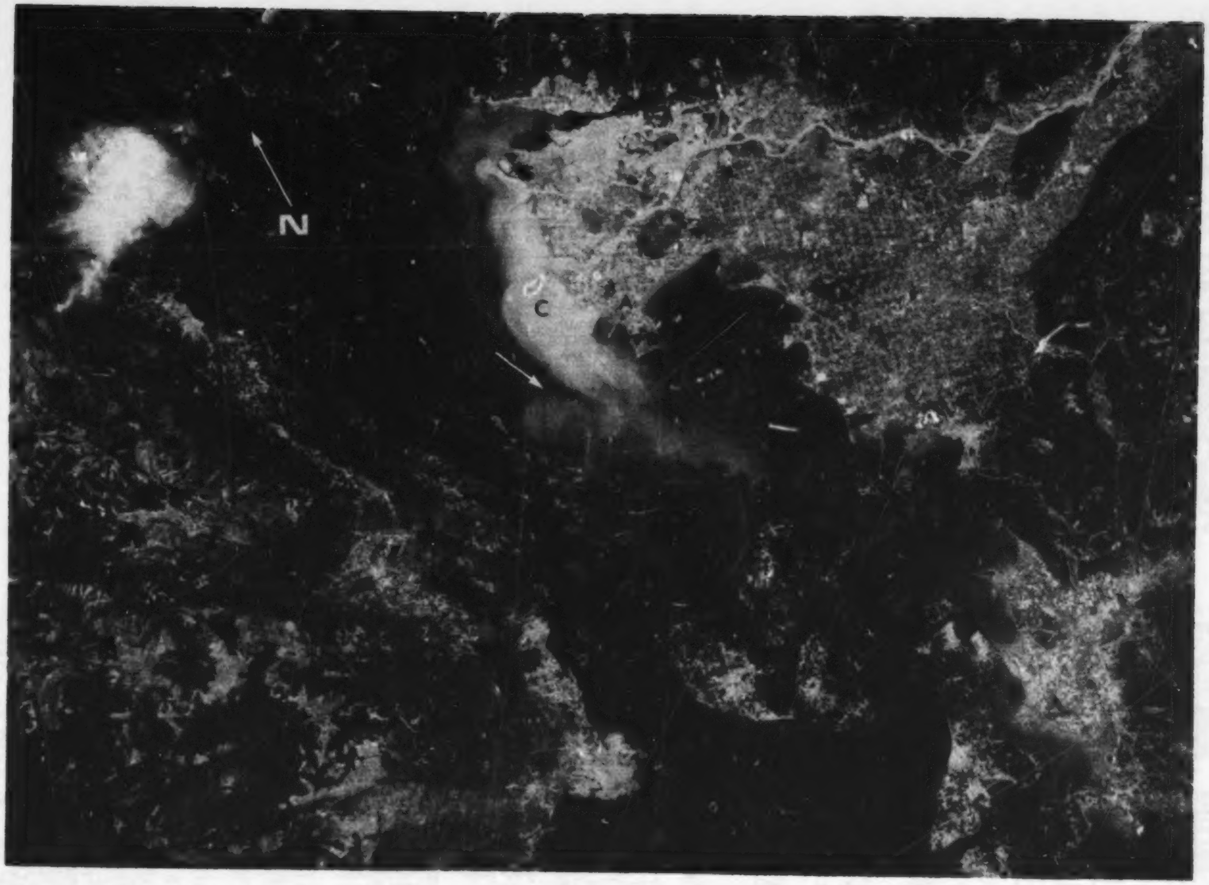

Figure 52. The Roberts Bank Causeway in British Columbia effectively diverts Fraser River silt laden water away from the shoreline. The causeway is about 2 mi (3.2 km) long. An environment atypical of the rest of the delta has developed down current of the causeway. The letter A marks the Roberts Bank Causeway, and B marks the Tsawwassen Causeway. The letter C indicates the Fraser River silt plume. The arrow denotes direction of flow. Photograph by the United States Geological Survey.

elevation relative to water level. Such changes can affect marsh plant ecology. An example is the different elevation requirements of _Spartina alterniflora_ and _Spartina patens_ in northeastern marshes.

Causeways may possibly result in disruption of fish and whale migration. According to Brisby (1977), whale migration was slightly disrupted by the causeway leading to Rincon Island, California.

Cumulative effects. The cumulative effects of bridges and causeways are referenced in the literature about the Florida Keys. The case study of this area should be consulted.

Structural and Nonstructural Alternatives

Bridges and causeways can be designed to respond to the physical and environmental surroundings in which they are built. Bridges can be placed on piling or piers shaped and spaced to provide minimum interruption of alteration of water flow. Bridge spans can be designed with longer lengths to reduce the number of piers or support structures in the water; however, a long span length may make the structure more costly to build. Causeways can be designed with culverts or open channels through the structure to allow water circulation. Causeways can be replaced by open pile structures instead of fill to allow nearly unhindered circulation of water.

Besides various methods of designing and building a bridge to alter the impact,there are some alternatives available. The most common structural alternative to a bridge is a tunnel. After construction,a tunnel provides no interference to water flow or circulation and no interference with the substratum or intertidal zone. If the tunnel is placed in a dredge trench,there might be substantial alteration of the substratum during construction, as well as other problems normally associated with the dredging or underwater excavation. As a general rule, tunnels are significantly more expensive than bridges.

There are several nonstructural alternatives to bridges. One, of course, is routing of the highway or railway over existing bridges or by circuitous routing not requiring a bridge. Another nonstructural alternative is to use a ferryboat instead of a bridge.

Tunnels and rerouting are also alternatives to the causeways, although a tunnel is so much more costly than a causeway that it is a theoretical rather than a practical alternative. Since the causeways normally cross marshes or shallow water, it is unlikely that a ferryboat would present a viable alternative in many instances. Structures associated with ferryboats, such as piers, also have environmental impacts. In addition, the convenience of a bridge relative to a ferryboat is obvious.

Regional Considerations

The only specific regional considerations mentioned in the literature were in reference to the Overseas Highway through the Florida Keys in Coastal Region 4. The case study should be consulted for further information.

CASE HISTORY STUDIES

This section contains summaries of cases where shoreline structures have been installed and the subsequent modifications to the environment. Case histories were selected to cover each of the coastal regions in this study and, where feasible, the structures which cause permit review personnel in each region the most difficulty. Some of the case histories are well-documented, and others are very sketchy. In some cases no information existed and hypothetical case histories were formulated. In each instance the case histories reflect the type of concerns that should surface in the permit review process.

CASE HISTORY - SMALL CRAFT HARBORS IN COASTAL REGION 1 -NORTH PACIFIC

Information pertaining to a specific harbor and location is not sufficient for the presentation of an actual case history in Coastal Region 1. A significant amount of the literature about small craft harbors in Coastal Region 1 is related to marina design and its effect on water quality and salmon migration. Four marinas in the Puget Sound area of Washington State will be compared to illustrate the impact of marinas in the Coastal Region 1. The four marinas are Edmonds Marina, Des Moines Marina, Kingston Marina, and Shilshole Marina. Maximum wave height in this area is approximately 6 ft (1.8 m). The tidal range is around 10 ft (3 m). Northwesterly winds are common in the summer (Rickey 1971).

Edmonds Marina consists of two attached rubble mound breakwaters protecting two marina basins (Figure 53). The entrance is located between these breakwaters. The shoreline is bulkheaded and two timber pile breakwaters extend from this bulkhead shoreward of the entrance separating the two basins. The basins are dredged to -12 ft MLLW or -3.7 m (Nece et al. 1975). There are 825 boat berths in the two basins and about 25% to 30% of the surface is shaded by floating piers. The municipal primary sewage treatment plant outlet is located just north of the marina and another large storm drain outlet is located to the south. The parking lot storm drains empty into the basin.

Heiser and Finn (1970) indicated that there was evidence of "impoundment"; but because of the location of the marina and the large entrance, the tidal exchange was adequate for reasonable water quality. Problems might arise from a spillage of petroleum materials within the basin because the materials would be held in the marina by winds blowing north or south toward the sides of the breakwaters. Observations by Heiser and Finn (1970)showed that pink and chum salmon fry were concentrated inside the marina in greater numbers than along adjacent natural shorelines. They do not know if the harbor acted as a trap for the fry or if they preferred the confines of the harbor.

Des Moines Marina consists of a single basin with a rubble mound breakwater leaving a dredged channel opening facing north. The basin is dredged to -12.6 ft MLLW (-3.8 m). The surface area of the marina is approximately 20 acres (8 ha) and about 25% of the surface is shaded by floating piers (Nece et al. 1975). Two residential storm drains and the parking lot drains empty into the basin. The location of the entrance is not conducive to the tidal exchange. Northerly winds are common in the summer and will cause interference with the outward movement of the water (Rickey 1971), resulting in stagnation at the southern end of the marina basin (Heiser and Finn 1970).

Kingston Marina consists of a dogleg rubble mound breakwater extending from the north shore, then angling twice at approximately 45° to protect the front of the marina. The south side of the marina consists of a large entrance. Because of this large opening, the water quality of the marina is relatively good. The large open area allows adequate tidal exchange and good movement of surface water out of the marina with northerly winds (Heiser and Finn 1970). Heiser and Finn (1970) observed

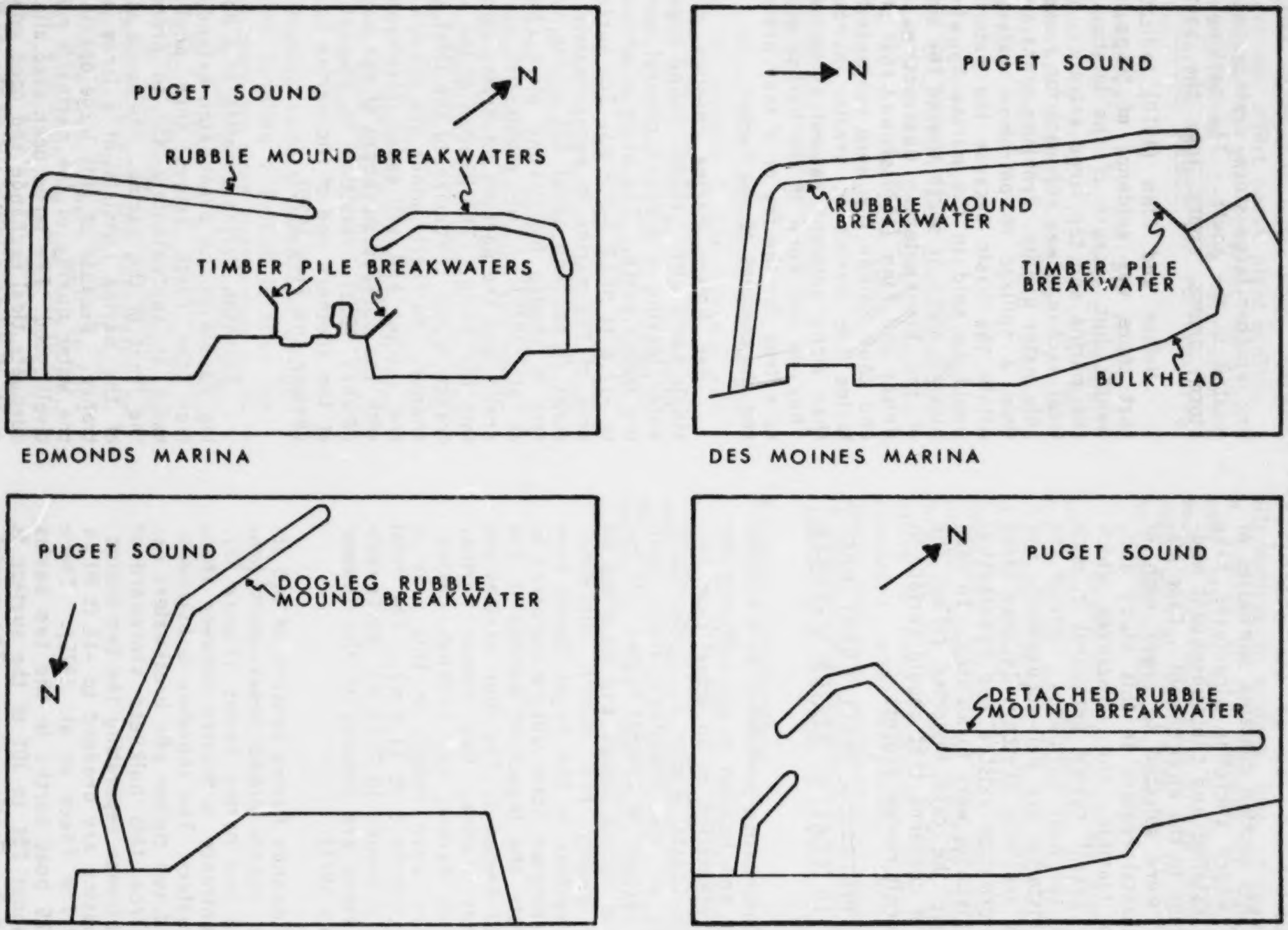
PUGET SOUND
N
RUBBLE MOUND BREAKWATERS
TIMBER PILE BREAKWATERS
EDMONDS MARINA
N
PUGET SOUND
RUBBLE MOUND BREAKWATER
TIMBER PILE BREAKWATER
BULKHEAD
DES MOINES MARINA
PUGET SOUND
DOGLEG RUBBLE MOUND BREAKWATER
N
KINGSTON MARINA
N
PUGET SOUND
DETACHED RUBBLE MOUND BREAKWATER
SHILSHOLE MARINA

Figure 53. Four different marina designs in Puget Sound, Washington. Diagrams are not to scale.

pink salmon fry within the marina in large concentrations.

Shilshole Marina is designed with a detached rubble mound breakwater. This allows for openings at both ends of the marina, as well as good tidal exchange and surface water movement. This design also facilitates easy passage for salmon.

Washington State Department of Fisheries (1971) recommends the use of open structures, as opposed to solid fill, to minimize impact on fish and shellfish in this region. Where solid structures are used, breaches should be provided to allow salmon fry passage without going into water greater than 12 in (30 cm) deep at all tidal levels. Shilshole and Kingston Marinas are more conducive to salmon fry migration because they do not restrict passage to the extent of Edmonds and Des Moines Marinas. Shilshole Kingston Marina has a particularly favorable design with the detached breakwater allowing salmon passage at both ends of the marina.

Edmonds Marina and Des Moines Marina are examples of marinas with "restrictive breakwaters" (Heiser and Finn 1970). They inhibit water circulation under normal circumstances and could result in rather serious effects if a spillage of toxic materials occurred. Marinas such as Kingston and Shilshole allow for more rapid dilution which can reduce such hazards (Heiser and Finn 1970). Edmonds Marina has an added disadvantage in that it is located close to a sewage outfall. Stockley (1974) recommends that marinas not be located closer than one-half mile to primary sewage plant or industrial waste outfalls.

CASE HISTORY - JETTY IN COASTAL REGION 1 - NORTH PACIFIC

Tillamook Bay, located about 50 mi (80 km) south of the mouth of the Columbia River, is Oregon's second largest estuary. It is about 6 mi (10 km) long and varies in width to a maximum of 3 mi (5 km). Over half the area of the estuary can be considered tidelands (U.S. Army Engineer District, Portland 1975b). Tides are diurnally unequal with a range of about 7.5 ft (2 m) in the bay (Terich and Komar 1973). Bayocean peninsula, a narrow sand spit about 4 mi (6 km) long, extends from the channel entrance at the north end of the bay south to Cape Meares, a rocky headland (U.S. Army Engineer District, Portland 1975b). Longshore currents are southerly from May to November and northerly from January through April. Net littoral transport is thought to be near zero. The tidal currents at the inlet are strongly influenced by the geometry of the inlet and bay (Terich and Komar 1973).

No prejetty data exist for environmental conditions at Tillamook Bay. The U.S. Army Engineer District of Portland (1975b) described the present setting in its environmental impact statement on dredging and jetty maintenance. Water quality is moderate to high; local turbidity is sometimes caused by high runoff conditions in incoming rivers. No complete inventories of fish and wildlife resources of the area exist, although considerable data are available. Both salt and freshwater fishes are present and the bay is a migration route for anadromous fish. Herring and other fishes spawn in the estuary. Dungeness crabs, oysters, clams, and shrimp are abundant, providing major recreational activities. Eelgrass beds are found in several areas of the estuary.

The history of the two jetties at the mouth of Tillamook Bay, Oregon (Figure 54), is amply documented. Early diaries, photographs, newspaper articles, and government documents describe the area before jetty construction, following construction of the north jetty and after construction of the south jetty. Unfortunately, these sources of information neglect to depict the original biology or to describe biological changes which have occurred over the years. History of physical changes influenced by the jetties is easily found, but changes in the biota must be inferred.

A journal of an early explorer, written in 1788, describes Tillamook Bay (Terich and Komar 1973). The entrance

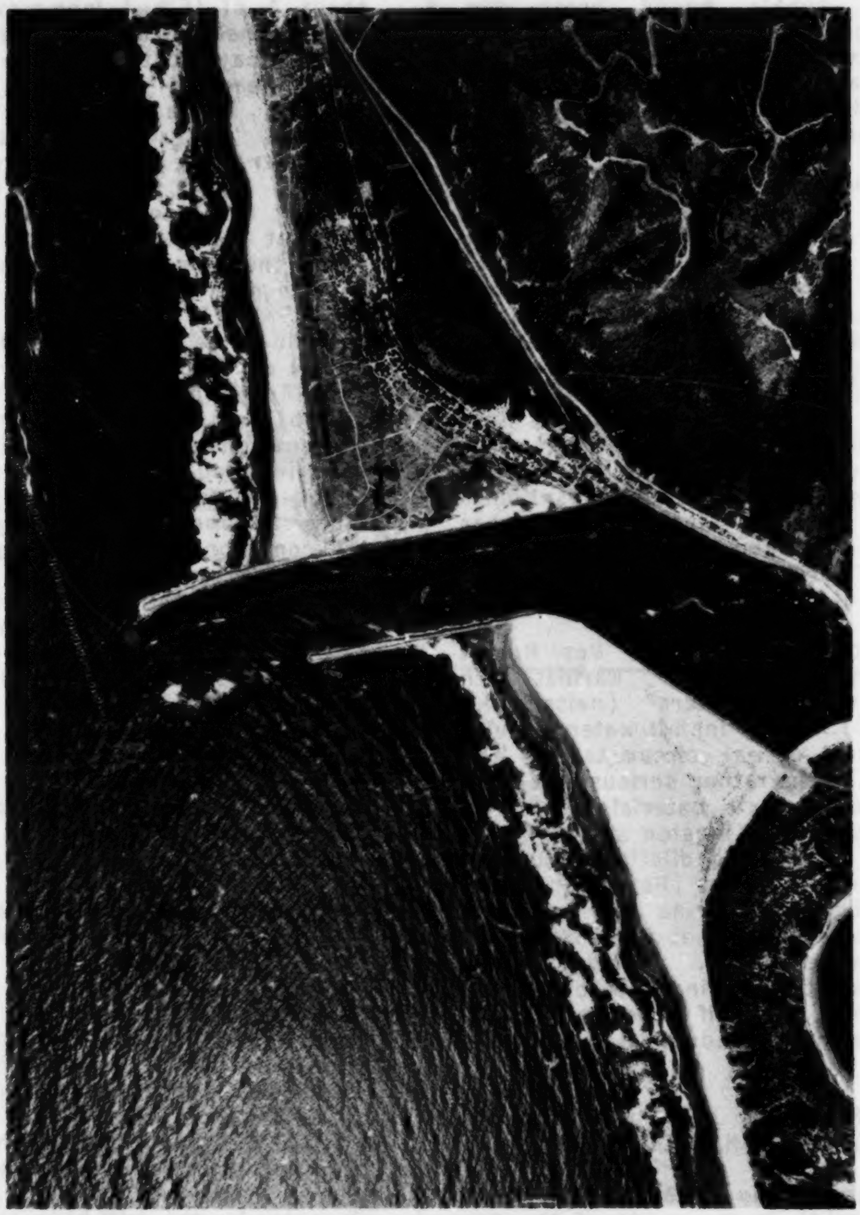

Figure 54. Tillamook Jetties, Tillamook Bay, Oregon. Bayocean Spit extends south from the south jetty at center of the picture. Photograph courtesy U.S. Army Engineer District, Portland, Oregon.

was narrow, with a dangerous shoal and rapid tides. This situation continued through the nineteenth century. In 1888 the U.S. Army Corps of Engineers reported that there was no reason to improve the channel entrance. Fifteen years later, the north jetty was proposed to control the ebb current (Terich and Komar 1973). The north jetty was completed to a length of 5,400 ft (1,646 m) in 1917 at a cost of $776,000. It incorporated 429,000 tons (389,180 metric tons) of stone. It was extended 300 ft (91 m) in 1933 (Terich and Komar 1973). No cost information on the extension was found.

By 1921,four years after the north jetty was constructed, the channel had migrated to a new position against the jetty, and dredging was later required to keep it open (Kieslich and Mason 1975). The hazardous channel conditions ultimately led to the construction of a second, longer jetty on the south side of the entrance beginning in 1969 (Terich and Komar 1973). The south jetty, completed in 1974, cost about $11.3 million (Anderson 1975). Total volume of stone used is not known, but Anderson (1975) reports that it was considerably more than had been estimated. This underestimation of material required was largely due to problems encountered during construction.

The jetty was built on the natural sand bottom. Though allowances were made for moderate sand loss due to the crosscurrent scouring during construction, the magnitude of this loss was grossly underestimated. At the halfway point in construction, the entire quantity of bedding material had been used. Strong currents around the advancing end of the jetty were washing out bedding material and sand to a depth of 30 ft (9 m) for about 300 ft (91 m) beyond the jetty tip. This problem was solved in part by eliminating bedding material and dumping large 200-lb (90-kg) to 5-ton (4.5-metric ton) core stone directly on the sand bottom and by working double shifts to accelerate the construction process (Anderson 1975).

Kieslich and Mason (1975) state that design objectives for jetties are to minimize undesirable effects of wave action on navigation and to eliminate the necessity for artificial channel maintenance. The latter is usually achieved by either preventing littoral drift from entering a channel or concentrating ebb currents so that their natural scouring action is enhanced. Apparently neither of these objectives has been achieved by the Tillamook jetties. The channel required dredging a few years after the north jetty was constructed (Kieslich and Mason 1975). In 1975, the Portland District, U.S. Army Corps of Engineers prepared an environmental impact statement for miscellaneous activities, including channel dredging, in Tillamook Bay.

Another factor in the construction of the south jetty was local desire for a means of halting erosion of Bayocean Spit. Following the extension of the north jetty, erosion apparently accelerated on the long, narrow sand spit (Terich and Komar 1973). Few records were kept previously, so it is unknown whether or not the construction of the north jetty increased erosion of the spit. It is known that the three-fathom contour moved 1,500 ft (457 m) closer to the spit between 1885 and 1939. This caused increased nearshore wave energy and concomitant erosion potential(Terich and Komar 1973). Historical records show definite changes in the shoreline both up and downdrift of the bay mouth following construction of the north jetty. Updrift sand accretion occurred behind the jetty, while the shoreline of the downdrift spit retreated due to erosion (Komar et al. 1976). The spit eventually became so narrow that a storm in 1939 opened gaps which allowed the sea to enter the bay. In 1952, a storm broke through and left a 0.8 mi (1.2 km) breach near the broad south end of the spit. This was later diked, but for some time there were essentially two entrance channels into the bay (Terich and Komar 1973). Recent information seems to indicate that erosion of the spit has slowed since construction of the south jetty (U.S. Army Corps of Engineers, Portland 1975).

The effects of the Tillamook jetties on the biota of the area can only be inferred since no quantitative before-

and-after studies were made. Altered currents within the estuary may have caused changes in sedimentation, salinity, and water temperature patterns. Erosion probably eliminated some sandy shore habitats, while accretion created others. The jetties provide a substrate for sessile and cryptic organisms and fish communities associated with the submerged structures. Turbidity,caused by scour, may have affected organisms in the area, and the confined channel may be a less than optimum environment for migrating smolts.

In relation to the human environment,the presence of the jetties has apparently enhanced the area as a beach recreation and sport fishing area. Stabilization of the entrance channel allows fishing boats access to the harbor and the sandy area behind the north jetty provides clamming and fishing. The jetties are extensively utilized by fishermen. Erosion of the Bayocean Spit has been blamed on the presence of the north jetty, so the loss of habitat and real estate may be a negative impact.

Channel maintenance dredging, inclusion of weirs in jetties, bypassing of sand, or no action at all are alternatives to the construction of jetties such as those of Tillamook Bay. If the inlet is to remain navigable, the no-action alternative is eliminated from consideration. Channel maintenance dredging disturbs the existing environment. Disposal of dredge spoils on land or in the estuary is generally considered unacceptable and sea disposal preferable. Thus, sand would be permanently lost from the area. Sand placed on downdrift beach would cause some temporary loss of habitat of intertidal organisms, but might slow erosion on the Bayocean Spit. Turbidity and resuspended sediments could affect water quality. Frequent dredging would be necessary and costly.

If an inlet must be stabilized, it appears that no acceptable alternatives to jetties exist. The impact of jetties on the physical and biological environment could be lessened by reducing their interruption of littoral drift. Weirs, placed at intervals along a jetty's length, and bypassing of sand would serve this purpose. This would reduce the erosion of the shoreline downdrift and accretion updrift. Whether the weirs would lead to the necessity for more frequent channel dredging would require site-specific study.

Careful studies of potential effects should be conducted before jetty construction is begun. Too often an inlet has been stabilized without thorough knowledge of effects on other aspects of the local environment.

CASE HISTORY - BULKHEADS IN COASTAL REGION 2 - SOUTHERN CALIFORNIA

Relatively little information was available concerning the bulkheads in Coastal Region 2, except some general observations on the effects of bulkheading and the other protection measures (Ploessel 1973, Carlisle 1977).

Bulkheads and seawalls are used in California for the same purposes as elsewhere in the country. They contain landfill and protect the bulkheaded shoreline from erosion. They also provide mooring.

Effects of bulkheads and seawalls on the biota of California are not well documented, but a high incidence of red tide has been observed in harbors which have poor water circulation as a result of bulkheading (Carlisle 1977). There is obviously a loss of habitat in areas which are filled, and intertidal communities may be severely affected if a bulkhead is built below mean high water. Scouring at the foot of a bulkhead is a physical impact which affects the benthic community in the vicinity of the bulkhead. The vertical wall of the bulkhead may also inhibit migration of certain organisms from the water to the shore (Carstea et al. 1975a) or along the shoreline.

Bulkheads and seawalls can have significant effects on human use of an area. Bulkheads in industrial or residential areas may increase boat traffic by providing mooring facilities. Seawalls on the open coast may restrict human access to beaches and may result in erosion of existing beaches.

The ecological effects of a bulkhead or seawall may be considerable. Shorelines are often inherently unstable and the structure of their biological communities reflects this instability. The erosion which bulkheads are designed to halt is a natural process to which the communities are adapted. Halting the erosion will alter the natural communities. Alternative structures, such as revetments of riprap, will also alter natural communities by providing a different type of substrate. However, riprap has several advantages over sea walls. Erosion of areas on the borders of the riprap may not be as severe as with bulkheads or seawalls. The major advantage of a vertical structure over a properly installed revetment is the provision of mooring facilities or cosmetic treatment of the shoreline.

When the bulkheads or seawalls are proposed in this coastal region,adequate consideration must be given to a number of important factors. First of all, given the existing littoral processes, determine where erosion and accretion will occur after installation of the structure. If erosion or accretion in an important habitat or navigable waters will result,then one can anticipate additional maintenance needs, such as beach nourishment or dredging,or the construction of additional structures. Secondly, based on the expected physical impacts of the structure, determine which aspects of the biotic community will be affected and the extent of the impact. For instance, if an area containing the marsh grass is to be bulkheaded and filled, many biotic effects can be predicted - such as reduction in the amount of primary productivity by marsh grasses and, consequently, a reduced crop of living and dead plant tissue for consumption by other organisms. Valuable spawning or rearing areas might also be removed. Each situation is unique and must be considered separately.

CASE HISTORY - SMALL CRAFT HARBORS IN COASTAL REGION 2 - SOUTHERN CALIFORNIA

A considerable amount of information is available in literature on small craft harbors in Coastal Region 2. Benthic studies were conducted by Reish (1961, 1962, 1963) from May 1956 to April 1962, regarding the benthic fauna and fouling communities in Alamitos Bay Marina following construction. These studies will be used as a base for a case history of Alamitos Bay Marina.

Alamitos Bay Marina is located in Alamitos Bay in Long Beach, California. The first marina basin was dredged from land beginning in late 1955. The basin was dredged to a depth of -12 ft (-3.7 m) mean low water and had a surface area of 12.5 acres (5 ha). In early 1956, after bulkheads had been constructed, the basin was filled with water. Further dredging was conducted in the central part of the basin. Boat mooring began in early 1957. Reish (1961) reported results of benthic sampling from May 1956 to August 1959.

The substrate of the first basin was originally gray clay containing bits of mica. In late 1957, black sulfide mud was discovered at one of the sampling stations. By summer of 1958, all sample stations had a layer of black mud containing a sulfide odor. This may be attributed to poor circulation causing a decreased oxygen supply. The number of benthic specimens collected varied quite noticeably during the first 2.5 yr of study with an increase after the basin filled with water followed by a precipitous decline. The lack of water circulation may have been the cause of the decrease in population that occurred in the spring of 1957. Low oxygen levels were discovered above the basin floor. Another possible cause of the benthos reduction is pollution caused by the boats in the basin. Benthic species composition within the basin was relatively constant over the rest of the study period and there was no indication of succession. Sixty percent of the species and 87% of the specimens collected were polychaetes (Reish 1961).

In 1959, the dredging of three more basins and the main channel began. Basins were dredged to -12 ft

(-3.7 m) mean low water, while the channel was dredged to -15 ft (-4.6 m) mean low water. Cement bulkheading and rock riprap were used for the sides of the marina. Benthic studies were conducted by Reish (1963) from August 1959 to April 1962, following the completion of dredging of the three additional basins and the channel. No benthic animals were found in the first samples taken following the dredging; specimens were found in samples taken in September 1959. Species numbers increased rapidly for the first 9 mo after that time, then held constant in the channel for the following 14 mo (Reish 1962). Over 50% of the species collected were polychaetes. Over the period of the study, no significant decrease in population occurred after about 1 yr in the first basin and in the inward portions of the additional three basins. This drop in species was related to a drop in dissolved oxygen and appearance of sulfide odor. These findings reinforced Reish's theory that poor water circulation was the cause of the decrease, since the water circulation in the channel was not restricted. According to Reish (1963), it apparently takes about 1 yr for the effect of limited water movement to alter the benthic environment of a newly established marina. No successional patterns of benthos were observed.

Reish (1961) also observed that succession of attached organisms did occur on the floats in the marina. The apparent climax community of *Mytilus* and *Ulva* was noted after the floats had been in the water for 6 mo. Up to 30 associated species might have been present. Reish (1962) notes that succession on solid substrates in the southern California waters is more rapid than what has been observed in other geographical areas.This may be due to longer breeding seasons and relatively restricted annual water temperature ranges.

Because of the apparent correlation between benthic population decrease and poor water circulation, it is recommended that measures be taken to maintain proper circulation in marinas. Poor water circulation affects the benthic community and may also adversely affect fishes, shellfishes, and other aquatic life in the area.

CASE HISTORY - BULKHEADS IN COASTAL REGION 3 - GULF OF MEXICO

Within the Gulf of Mexico, a number of studies are available documenting the effects of bulkheads or seawalls on certain components of an ecosystem (Corliss and Trent 1971, Gilmore and Trent 1974, Mock 1966, Moore and Trent 1971, Trent et al. 1972, 1976). These studies are primarily concerned with structures on the coast of Texas, but the results are generally applicable along the Gulf coast of the United States.

The purpose of bulkhead or seawall construction in this region is to provide protection of upland areas from erosion and also to provide waterfront real estate. This latter function is achieved by constructing a bulkhead along a vegetated shoreline and then filling the area behind the bulkhead to provide land for development. Such artificial creation of real estate is common in Galveston Bay, Texas, and in Florida. Bulkheads also provide mooring facilities.

The creation of bulkheaded waterfront housing developments in this region has clear socioeconomic significance, regardless of the level of environmental impact. Their success in providing desirable real estate is obvious. Alternate structures are generally not considered because of the economic benefits gained from filling behind a bulkhead or seawall. Their effects on coastal processes and the biota require more detailed study.

Trent et al. (1976) studied an area in the West Bay of Galveston Bay, Texas, which had been a natural marsh before bulkheading. The marsh was altered by channelization, bulkheading, and filling. The altered area consisted of a series of dead end canals with houses built on the strips of land separating the canals. Approximately 111 acres (45 ha) of emergent marsh vegetation (primarly *Spartina alterniflora*), intertidal mud flats, and subtidal areas were converted into about 79 acres (32 ha) of subtidal habitat by the development (Trent et al. 1976).

Phytoplankton production, oyster production, benthic macroinvertebrates, fish, and crustacean abundance were studied in an open bay area, the bulkheaded canal area, and in adjacent natural marsh area. Primary production of phytoplankton was higher in canal than marsh areas, and production in both areas was much higher than in the bay (Corliss and Trent 1971). Oyster setting was 14 times greater in the natural marsh than in a canal area. The faster growth and lower annual mortality rates in the natural marsh were also reported by Moore and Trent (1971). Benthic macroinvertebrates were numerically slightly more abundant and volumetrically over twice as abundant in the marsh than in the canals. The lowest abundance was in the bay. However, when individual phyla were considered, numeric and volumetric abundance varied by area (Gilmore and Trent 1974). More finfishes and crustaceans were caught in the marsh than in the canals and catches were much higher in both areas than in the bay. Brown shrimp (Penaeus aztecus), white shrimp (P. setiferus), and spot (Leiostomus xanthurus) were most abundant in marsh; and largescale menaden (Brevoortia patronus), Atlantic croaker (Micropogonias undulatus) and bay anchovy (Anchoa mitchilli) were most abundant in canals (Trent et al. 1972). These six species comprised 89% of the total catch. Mock (1966) compared penaeid shrimp production in a bulkheaded and natural area in another area of the Galveston Bay system. He found greater shrimp production in the natural habitat.

Numerous physical differences between the altered and unaltered marsh areas were noted. Substrates in the canal areas had a higher silt and clay content than the marsh, and the amount of organic detrital materials in marsh substrate was twice that found in the canals (Trent et al. 1972). Average temperature, salinity, total alkalinity, and pH were similar between the marsh and canal areas. The average dissolved organic nitrogen was highest in the marsh and may have been due to cattle grazing near the marsh. Average total phosphorous was highest in the canals of the housing development, but was variable across time. Average levels of dissolved oxygen and surface turbidity were lowest in the canals, and dissolved oxygen levels dropped to extremely low levels at sampling stations farthest from the bay during the summer months.

In general, productivity was higher in the marsh than in canal areas and lowest in the open bay. Plankton blooms followed by low levels of dissolved oxygen, high nutrient levels, fish kills, and depressed oyster, benthic macroinvertebrate and shrimp production in the summer months indicated the presence of eutrophic conditions in canal areas of the housing development. Moore and Trent (1971) noted that eutrophic conditions probably develop more rapidly in housing development canals than in natural marsh areas because of high nutrient levels, increased phytoplankton production, and a reduction in water circulation and exchange.

Reduced productivity in bulkheaded canals may not be directly attributable to bulkheads, but rather to the increased human usage of the area and the removal of marsh habitat. Human use of bulkheaded and filled areas is generally increased in terms of housing and boating.

From a biological standpoint, bulkheading in this coastal region alters existing communities and may eliminate some species entirely. The energy base of the community changes considerably with the elimination of marsh grasses. There are no satisfactory alternative structures for the creation of new real estate. However, existing land may be protected from erosion by the use of revetments or by planting vegetation. When placing bulkheads or seawalls, it is desirable to locate them as far upland as possible, preferably above mean high water.

CASE HISTORY - CAUSEWAYS IN COASTAL REGION 3 - GULF OF MEXICO

The information available about causeways in Coastal Region 3 is very limited. Clewell et al. (1976) conducted a study of seven fill-road sites on the northern Gulf coast of Florida. Sites were located in five tidal salt marshes in Wakulla, Taylor, and Dixie counties. This study will be used as a case history of causeways in Coastal Region 3.

According to Clewell et al. (1976), tidal marshes in the area studied exist "where waves penetrate only during severe storms and hurricanes." Marshes are periodically flooded as a result of tidal sheet flow. The height of high tide is dependent on lunar positions and is, therefore, variable. A marsh located at a higher elevation may not be inundated as often as one at a lower elevation. The sites that are inundated daily usually have a uniform salinity similar to that found in tidal creeks or rivers. Sites not flooded daily have a higher salinity due to evaporation. Sites high enough in elevation to receive more fresh water from runoff and rain than the salt water inundation have low salinities. The vegetation is dependent upon the salinity levels of the site.

The distribution of three mollusc species sensitive to particular regimes of salinity and inundation were studied. These species reacted to disturbances by alterations in density. Plant zonation was also determined along with salinities and elevations.

The Porter Island site involves a paved fill-road built 22 yr prior to the study that traverses a 1.5-mi (2.4-km) long marsh protruding into Apalachee Bay. The fill is not culverted. The only opening consists of a 25-ft (7.6m) long bridge span. Fill canals run along the entire length of a roadway on both sides. The study revealed that other than the presence of the roadway and canals, the marsh environment was not adversely affected because tidal inundation occurs independently on both sides of the unculverted marsh since it is bounded by Apalachee Bay on both sides.

The Levy Pond site consists of a marsh separated from a creek by an unculverted fill-road built 38 yr prior to the study. The roadway has blocked the sheet flow so that the marsh (Levy Pond) contains fresher water than the tidal creek on the other side of the fill-road. Photographs taken from years after construction showed that various salt-intolerant plant species have grown in Levy Pond. No vegetation can be seen in similar ponds on the seaward side of the road. At the time of the Clewell et al. (1976) study, Levy Pond was "completely choked with cattails, sawgrass, and other emergent marsh species, all characteristic of fresh water or very slightly brackish habitats."

The Evans Creek site contains a fill-road,built 38 yr prior to the study, that traverses a tidal creek (Evans Creek) approximately 0.5 mi (1.3 km) from its mouth. The salt marsh on the landward side is isolated from the creek except for a box culvert (5 x 5 ft or 1.5 x 1.5 m). The creek was ditched to facilitate tidal inundation of the landward side of the road. Only slight differences in salinity, animal density, and vegetational zonation were discovered between the landward and seaward side of the fillroad. Clewell et al. (1976) state that it is uncertain if these differences are due to the roadway or if they always existed between the two areas. It is suggested that the ditching "increased the frequency of tidal flooding but decreased the length of time that the marsh was inundated in each tidal cycle." They suggest that culverts might be substituted for ditching to maintain more natural inundation and drainage in such marshes.

The Cedar Island study involves a north and a south marsh. The two sites are landward of a fill-road, built 8 yr prior to the study, that runs parallel to the coast 0.3 mi (0.5 km) inland. The north site can only be inundated by the sheet flow. Only one culvert opens up to the seaward side of the road. A ditch and tidal creek flowing into a culvert allow inundation at the south site. The results of the study indicate that sheet flow was blocked at the north marsh except when severe storms occurred. This allowed for the invasion of salt-intolerant species. The effects of the fill-road and ditching in the south marsh appeared to be similar to the Evans Creek site.

Two sites were also investigated at Cow Creek. Both of the sites are landward of a fill-road completed 4 yr prior to the study and paralleling the coast. What is referred to as the "open area" is 1 mi (1.6 km) from the Gulf along Cow Creek. The study area is connected to the seaward side by a 6-ft(1.8-m) wide culvert. Salinity, plant zonation, and pattern and abundance of molluscs were the same on both sides of the road and are, therefore, assumed to be unaffected by the fill-road.

What is referred to as the "closed area" is approximately 0.8 mi (1.3 km) from the Gulf. A 3-ft (0.9-m) wide and 12-ft (3.7m) wide culvert facilitates the drainage. Fill canals are located on both sides of the roadway. Sheet flow appears to be restricted from the landward side of the roadway, as evidenced by the presence of salt intolerant species. Clewell et al. (1976) state that the canals are intercepting much of the incoming tidal water.

Clewell et al. (1976) conclude that if the tidal flow through a fill-road is unrestricted, marsh will not be significantly affected, other than within the area where construction of the fill-road took place.

CASE HISTORY-BRIDGES AND CAUSEWAYS IN COASTAL REGION 4 - SOUTH FLORIDA

The State of Florida Department of Transportation (FDOT) in cooperation with the U.S. Department of Transportation - Federal Highway Administration (FHA) contemplates replacing 37 of the 44 bridges along 87 mi (140 km) of the Overseas Highway (State Road 5,U.S.1) from Key West to Key Largo. The localized impacts due to construction and operation and regional impacts due to cumulative affects of the many bridges and associated causeways make an interesting case history study. Impacts discussed in this case history study will be limited to terrestrial and aquatic impacts. Unless otherwise noted, the source of information is "Negative Declaration State Road 5 (U.S. 1) Bridge Replacements" (H.W. Lochner, Inc., Consulting Engineer 1975).

Around the turn of the century, Henry N. Flagler, one of the founders of Standard Oil and builder of the Florida East Coast Railroad from Jacksonville to Miami, decided to extend his railroad to Key West. The resulting single track Overseas Railroad, completed in 1912, covered a distance of 156 mi (251 km). In September 1935, a hurricane washed out the track and roadbed in the 30-mi (48-km) stretch from Key Vaca to Plantation Key. It was decided that the railroad would not be rebuilt.

Overseas Road and Toll Bridge Commission purchased the right-of-way and the associated physical assets and directed their efforts toward converting the remaining railroad structures to highway structures. The new highway was opened to Lower Matecumbe Key in 1936, to Big Pine Key in 1938, and to Key West in 1944. The bridge-causeway system supplies access between mainland and Keys for residents and vacationers. It carries an aqueduct which assures a supply of fresh water to the Keys.

Many of the bridge structures have deteriorated severely since construction more than 30 yr ago. Between 1963 and 1973, a total of $10,000,000 was spent for bridge repair. This sum equals the original cost of the highway system. It is estimated that maintenance costs for the period from 1975 to 1985 will be $84,000,000. In 1974, Congress passed a highway bill which appropriated $109,200,000 for the replacement project. In addition to the positive cost-benefit analyses between replacement and maintenance, there is definite concern that the deteriorating structures might experience structural failure, possibly causing loss of life or serious injury. It would also result in loss of access between the Keys and the mainland, as well as possible health hazards in the Keys due to a loss of the potable water supply.

The proposed reconstruction project will replace 37 of the 44 bridges which represents approximately 17 mi (27 km) of the 18 mi (29 km) of bridges in the Overseas Highway. Of the 37 bridges proposed for replacement,27 are the spandrel arch type, one consists of spandrel arch and pier sections, and the remaining 9 are composite pile type (Figure 49). The proposed bridge replacement will also involve the reconstruction of approximately 21 mi(34 km) of bridge approach. About 11 to 33 acres (5 to 13 ha) of submerged land will be filled.

The Florida Keys are composed of flat limestone formations with elevations ranging up to 15 ft (4.6 m) above mean sea level. About 95% of the land is less than 5 ft (1.5 m) above mean sea level. Shoal water commonly ranges up to 0.5 mi (1.3 km) offshore. Shoals are generally composed of the mangrove swamps, submerged turtle grass beds, and exposed limestone with little or no soil.

The islands lie just north of the Tropic of Cancer, with Key West being the southermost city of the contiguous United States. Key West is closer to Cuba (90 mi or 145 km) than to Miami (154 mi or 248 km). Hurricanes, which occur frequently in the Florida Keys, are probably the most significant climatological feature of the area.

The chain of 97 islands separates Florida Bay on the Gulf of Mexico side from Florida Straits on the Atlantic Ocean side. Relatively deep channels between the keys transport water between the Gulf and Atlantic Ocean. It was estimated that the construction of the original railroad system reduced the cross-sectional water area between islands by more than 50% (Bailey 1977), which reduced water exchange between Florida and the Atlantic Ocean. Salinities in the upper portion of Florida Bay are greater than 50 ppt for 9 to 11 mo of the year, as compared to 34 to 37 ppt in the Atlantic Ocean (Davis 1977). There are no historical records, but reduced flow between Florida Bay and the Atlantic Ocean may be a factor contributing to the salinity difference (Bailey 1977). Florida Bay system is shallow as compared to the contiguous Atlantic Ocean and experiences diurnal temperature changes of 10° to 15°F (5.6° to 8.3°C) during part of the year (Davis 1977). This large diurnal temperature fluctuation does not occur in the ocean. The difference in solar energetics in the Bay as compared to the ocean is probably also a factor contributing to the salinity differences.

The Florida Keys contain more endangered, threatened, and rare plant and animal species than any other region of the State. Thirteen major parks and wildlife refuges lie partially or wholly within the Florida Keys.

The extensive emergent mangrove forest and submerged turtle grass beds are vital habitat for the propagation of commercially and recreationally important species of fishes, shellfishes, and wildlife. Availability of habitat is the limiting factor for these populations. Protection of habitats is paramount to protection of plant and animal species.

After a lengthy series of public hearings, advisory committee meetings with concerned residents and Federal, State, and local agencies, FDOT and FHA issued a "Negative Declaration State Road 5 (U.S. 1) Bridge Replacements" (H. W. Lockner, Inc., Consulting Engineer 1975).

The negative declaration evaluated each bridge site separately, considering the following alternatives:

A. Continue to maintain existing bridge;
B. Remove existing bridge and construct new bridge on or near existing alignment;
C. Composite causeway structure;
D. Construct new bridge on Gulf or Atlantic side of old bridge.

Alternative A was easily eliminated based on economics and safety. Alternative C was carried to the final evaluation stage on nine bridges, but was eliminated based on possible adverse impact on natural and human environments. Alternative B or D was chosen for each bridge on a site-specific basis.

The environmental impacts addressed in the negative declaration were mostly localized in nature. They did, however, emphasize the role of habitat. Features of the project related to terrestrial and aquatic ecological impacts that were addressed include

- No unique vegetation will be removed.
- Some submerged land will be filled.
- Revegetation will be considered.
- Net impact of filling kept at a minimum by increasing bridge length and utilizing steep side slopes on approaches.
- Control of turbidity due to construction will be studied.
- Borrow from dry land will be preferred as compared to borrow from submerged lands and from the previously disturbed areas as compared to new areas.
- Offshore dredging for fill in vicinity of bridges not anticipated except where construction dredging may be required.
- If submerged borrow operations were undertaken, containment of the "dredge plume" would be an important concern.
- If dredging of marinas from the onshore areas is done, no connection should be opened until turbidity has dropped to safe levels.
- Holding borrow site depth to approximately 20 to 25 ft will be considered.
- Width of the fill will be minimized by using steep slopes.
- Structural retaining systems will be considered in some locations to reduce the area of bottom filled. Sheet pile walls or tie-back types will probably not be used due to potential washout.
- Air quality standards will not be violated.
- Where FHWA exterior noise criteria are expected to be exceeded, exceptions will be requested.
- It is improbable the runoff from bridge or road surfaces would violate State water quality standards.
- The possibility of spillage of toxic materials from trucks will be reduced because the road will be safer.
- Construction and maintenance of new bridges will be according to State Standard Specifications for "Prevention, Control and Abatement of Erosion and Water Pollution."
- The use of sediment traps during construction will be considered.
- Interim use of webbing, matting, mulching, and other mechanical means of erosion control will be provided for.
- Consideration will be given to special specifications for bridge demolition and material disposal.
- Consideration will be given to appropriate location of parking.
- Where mangroves are impacted, their associated organisms can move elsewhere.
- Retaining mangroves on the ocean side will be more important than on the Bay side because of their relative scarcity and wave protection function on the ocean side.

Many of the foregoing considerations can be considered as directed at localized impacts. After release of the negative declaration, FDOT negotiated with concerned natural resource agencies about regional considerations.

Several agencies felt that FDOT was missing a good chance to return the circulation patterns between Florida Bay and the Atlantic Ocean to the previous state that had existed before the Flagler railroad was constructed. As mentioned before, cross-sectional area between islands was reduced more than 50% by that project.

All concerned individuals seem to agree that the salinity difference is real, but that the contribution of the causeway to this situation is not known. Natural physical differences between the two bodies of water are probably a significant causative factor. Channelization of the Everglades in 1962 and resultant alterations of fresh water outflow to the Florida Bay is probably also affecting the salinity regime (Davis 1977).

There is definitely not agreement on whether increased flow between the two water bodies would result in an overall benefit.

Davis (1977) stated that there have been changes in the salinity of the estuarine areas of the Everglades from 0 to 12 ppt prior to 1940, up to 25 to 40 ppt presently. This has probably changed the nursery ground function of affected areas, but the nature of the changes is not known.

Numerous years of data show that the year-class strength of redfish in Florida Bay proper is positively correlated to high salinities in the spring, whereas the year-class strength of sea trout is positively correlated to low salinities in the spring. Alterations in springtime salinity might constitute a tradeoff between the population levels of these two fishes.

Pink shrimp and spiny lobster provide the two largest commercial catches in Florida. They are both highly dependent upon Florida Bay as a nursery. Recreational species, such as bonefish and tarpon, are also very dependent upon Florida Bay as a nursery. The effect of salinity changes in the production of these important commercial and recreational organisms is not known (Davis 1977).

It has been observed by Davis (1977) that the best coral reefs along the Florida Keys occur at the northern extremity where exchange of water with Florida Bay has always been minimal. John Pennecamp National Underwater Preserve is known worldwide and is located in this area. Coral is known to be very sensitive to altered salinities, temperature fluctuations, and turbidity and siltation. Waters flowing from Florida Bay to the Atlantic Ocean through the Keys' channels are high in salinity, have large temperature fluctuations and are relatively turbid and silty due to wave action in shallow areas. If water circulation was increased between Florida Bay and the Atlantic Ocean, there might be resultant impacts upon coral reef communities.

The FDOT has agreed to conduct a two-phase study of the possible causes of a potential remedial action for the hypersalinity problem in Florida Bay. The first phase will include studies to determine the relative contribution to the hypersalinity of the causeway area, natural physical processes, channelization of the Everglades, and other factors. It will also determine the possible results of various measures to alleviate the problem. The second phase of the study will be to project the biological consequences of possible remedial actions, such as increasing the flow between the Keys.

Another major concern regarding the project is that valuable turtle grass beds will be directly and indirectly (siltation) affected by dredging. After several meetings it was agreed that FDOT would mitigate turtle grass losses acre for acre (Bailey 1977, Hall 1977). The FDOT has conducted a study to delineate the turtle grass beds as they presently exist. A comparable study after construction will define the acres of turtle grass that will be mitigated.

Most of the shoals bordering the Keys contain flat limestone bottoms which do not have unconsolidated sediments and are, therefore, not suitable for turtle grass growth. During an interview with F. Bingham of the Florida Department of Transporation, it was pointed out that some of the best turtle grass beds in the Keys are in the old borrow pits which resulted from the construction of the railroad and original causeway (Figure 55). The depth of the borrow pits fosters sedimentation of organic material which serves as an excellent turtle grass substrate. It is not known, however, how long it takes for the turtle grass to establish itself in borrow pits (Hall 1977). The depth of the borrow pit probably affects its suitability for turtle grass growth and the time period necessary for turtle grass establishment. The acre-for-acre mitigation of turtle grass beds might possibly be accomplished by dredging a flat limestone bottom and allowing sedimentation and turtle grass establishment.

Environmental concerns surrounding the bridge replacement are many. Nearfield effects are somewhat classical

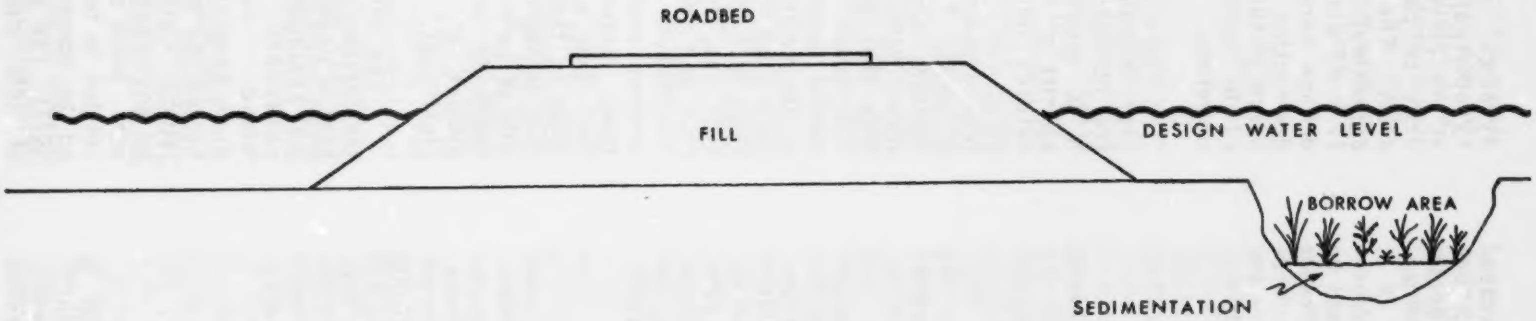
ROADBED
FILL
DESIGN WATER LEVEL
BORROW AREA
SEDIMENTATION

Figure 55. Cross-sectional view of a causeway constructed with fill material from a nearby borrow area. The sedimentation in the borrow area can foster seagrass growth in some situations in the Florida Keys.

of construction projects in the coastal environment. The farfield effects, such as the potential contribution to hypersalinity and associated ecological modifications, are not as well known. It is probable that potential effects of causeways on the marine environment will be debated for many years. At present the key issue controlling the replacement project is the potential loss of life or serious injury that could result due to structural failure.

CASE HISTORY - GROINS IN COASTAL REGION 5 - SOUTH ATLANTIC

Coastal region from Cape Canaveral to Cape Hatteras is characterized by barrier islands, marshes, and estuaries (Virginia Institute of Marine Science 1976). The barrier beaches are long, narrow sand beaches separated from the shore by embayments of varying widths up to 30 mi (48 km). Most of the shoreline lacking barrier beaches is also sandy and flat and is broken by estuaries and tidal marshes. The sand is fine and is easily transported by the sea. The natural beach erosion resulting from the storms and tides has been accelerated by the often carelessly planned placement of shoreline structures, such as groins, bulkheads, jetties, and breakwaters (Bruun and Manohar 1963).

Some assumptions can be made about an undisturbed barrier island a mile or more in length and separated from adjacent islands by wide inlets. Natural processes will cause erosion and accretion of sand at various points; the storm winds and tides will break through islands, opening a channel into the lagoon while the other channels will close. The barrier islands will, over time, change in shape, size, and topography. The plants and animals found there will, as they always have, adapt to these changes. Unfortunately, man is often not tolerant of normal shoreline dynamics. Beaches must be stabilized to provide recreation, real estate, industrial sites, or harbors.

Insufficient data were available to provide a case history, so a hypothetical situation was developed to demonstrate the effects of groins on shoreline dynamics in this coastal region. A hypothetical island is nearly breached at one point, so a groin is built downdrift to cause accretion at the weak area. The construction of the groin approximately 50 ft (15 m) long by 5 ft (1.5 m) wide causes little environmental damage because it is small. Turbidity, destruction of bottom habitat, and beach disturbance are minor when viewed in light of the extent of nearby shoreline.

There are effects which do not appear immediately. The groin interrupts the littoral transport of sand, causing it to accumulate updrift. The beach updrift of the groin grows higher and extends out nearly the length of the structure. The updrift area is protected from erosion forces by a broad expanse of sand. This does little harm to the resident organisms because it is a slow accumulation process and not different from that to which they have adapted. The beach recedes downdrift since its normal supply of sand now lies updrift of the groin. If unchecked, it will recede until a breach occurs and the sea flows into the lagoon. The natural process has, therefore, been displaced in time and space. To protect the human investment, another groin is built and another until the barrier beach is entirely protected by a vast groin field. Each time a minor amount of damage is done to the environment, a few square feet of habitat is lost. However, in the mile of barrier beach, there could eventually be as many as 50 groins. The amount of habitat lost becomes more significant.

One little discussed effect of beach stabilization on barrier island systems is that of changing the physical and chemical characteristics of the estuaries and embayments lying behind the barrier islands. Periodic wave overwash or dune breaching allows seawater to reach behind the islands, causing salinity variations. Plants adapted to such an altered environment survive, while others do not. When the beach is stabilized, succession is toward plants not well adapted to oceanic conditions (Dolan et al. 1973). The advantages or disadvantages of this situation depend on what is desired as an end result for that coastal area. The tradeoffs involved are discussed by Dolan (1966) and Dolan et al. (1973). Altered salinity regimes in the embayment can also affect life cycles and productivity of various aquatic organisms, although this has been little studied.

CASE HISTORY - BULKHEADS IN COASTAL REGION 6 - MIDDLE ATLANTIC

Within Coastal Region 6, a number of references are available on effects of bulkheads (Carstea et al. 1975a, Gantt 1975, Yasso and Hartman 1975, Chesapeake Research Consortium 1974, 1976, Givens 1976). Most of the existing information refers to Chesapeake Bay, but Yasso and Hartman (1975) discussed bulkheads in the New York Bight. The observations contained in the literature are broadly applicable within this region, even though specific flora and fauna will vary from location to location.

Bulkheads in this region are used primarily to protect upland areas from erosion and to stabilize the existing shoreline. Construction of bulkheads with either steel or wood sheeting is common.

Impacts in this region due to construction of a typical 150-ft (46-m) timber bulkhead and the associated dredging of 300 yd^3 (274 m^3) of fill were considered in a theoretical case history by Carstea et al. (1975a). In this case, it was expected that there would be no significant impact on water quality. The increased turbidity would not affect water quality significantly. There would be minor air quality and noise construction impacts, and some organisms would be directly eliminated by dredging and burial.

An alternative to the bulkhead construction is the use of a revetment. However, bulkheads provide mooring facilities which may be desirable in some situations.

Once in place, bulkheads provide protection for upland areas immediately behind the bulkhead; however, unprotected areas adjacent to the bulkhead may be eroded, and this can undermine the bulkhead from the sides. Carstea et al. (1975a) claimed that bulkhead construction would have a positive effect on water quality by stabilizing the shoreline and reducing erosion. However, Gantt (1975) stated that scouring may cause erosion at the toe of the bulkhead and that unprotected adjacent shorelines may erode because of the undissipated wave energy resulting from a bulkhead. Carstea et al. (1975a) conceded that the roughness coefficient will indeed decrease slightly with bulkheads yielding an increase in the velocity and the dispersion coefficient of the water, but stated that, if properly constructed and maintained, bulkheads will have no significant effects upon erosion, sedimentation, or deposition. On the other hand, one can expect alterations to littoral drift and currents, according to Gantt (1975). Carstea et al. (1975a) maintained that a small timber bulkhead would produce no significant increase or decrease in the storage capacity of the water body and no additional drift problems. The differences in the conclusions of these authors are considerable, but may revolve around a different perception of what constitutes a "significant effect." Furthermore, a single small bulkhead, such as the one considered by Carstea et al. (1975a), will have much less of an effect by itself than will many small bulkheads taken as a whole.

Biological impacts of bulkheads are dependent primarily on the location of the bulkhead, with upland locations providing the least damage. Construction below the mean high water line is more damaging, and construction below mean low water is most damaging. Filling behind a bulkhead will destroy organisms located there. Isolation of marsh grasses from tidal waters will cause a loss of part of marsh grass community (Carstea et al. 1975a). Loss of wetlands will result in the loss of detritus production, storage, and transfer of nutrients; loss of feeding, breeding and nursery areas for fish, shellfish, and the other organisms; loss of flow regulation and shore stabilization; and loss of habitat for the waterfowl and terrestrial species. Gantt (1975) noted the destruction of fringe marsh and shoreline when dredging occurs, along with a reduction in species diversity in the zone near shoreline; nutrient cycle changes leading to lower water quality; high oyster mortality in the vicinity of the bulkhead; reduction in invertebrate production; and prevention of recolonization by scouring action in front of the bulkhead. Wolcott (1977) reported that bulkheads prevented the ghost crab (*Ocypode quadrata*) from reaching dune areas where they burrow during cold weather.

A bulkhead provides docking facilities; however, it limits recreational activities associated with a natural coastline (Carstea et al. 1975a). According to Carstea et al. (1975a), even a small bulkhead will cause erosion of sand and shallow water on neighboring beaches. Eliminating the littoral zone may reduce productivity in an area and thus affect fishing. They estimated that there was generally little or no socioeconomic impact of bulkhead construction in this region.

From a biological standpoint, bulkheads are generally not desirable structures in this region. Reduction in the amount of marsh grass (*Spartina alterniflora*, *S. patens*) will result in a tangible loss of the estuarine productivity. Carstea et al. (1975a) estimated that a 150- ft (46-m) timber bulkhead, assuming a width of 20 ft (6 m), would destroy 3,000 ft^2 (914 m^2) of habitat. This would result in a loss of 1,230 lb (558 kg) of detritus per year. This amount of detritus could support approximately 9 lb (4 kg) of shellfish per year at 125 lb (57 kg) of shellfish supported per acre per year (Carstea et al. 1975a, cited by Isard, W. 1972. *Ecologic-Economic Analysis for Regional Development*. The Free Press, New York, New York).

It is possible to construct upland bulkheads which preserve wetlands and have a relatively minor effect on the coastal ecosystem. Each proposed bulkhead must be evaluated, based on its potential for damage, in light of community existing at the proposed site. To afford maximum protection to the coastal ecosystem each bulkhead should be considered not as a single isolated structure, but rather as an addition to an ever-growing complex of shoreline structures.

A possible alternative to bulkhead construction is the placement of riprap or other types of revetments, but these structures also have environmental consequences. If mooring facilities are desired, small piers may be substituted.

CASE HISTORY - SANDBAG SILL BREAKWATERS IN COASTAL REGION 6 - MIDDLE ATLANTIC

Sandbag sills are being tested under the auspices of the Virginia Institute of Marine Science as alternatives to, or complements of, groins in the Chesapeak Bay (Greer 1976). No quantitative biological studies were found and only a minimum of other information exists. However, since they are potentially a viable alternative to groins as shore protection devices, their use can be expected to increase.

Chesapeake Bay has a long history of shoreline erosion, primarily resulting from wind-generated wave action. Slowly rising sea level also contributes to this problem. Greer (1976) reports that the 270 million cubic yards (249 million cubic meters) of material were eroded from Virginia's Chesapeake Bay shoreline between 1850 and 1950. Bulkheads, revetments, and groins have been used in an attempt to retard or stop this shoreline loss, but they are often unsuccessful (Greer 1976). In addition, navigation channels are clogged by eroded sediment and valuable real estate is being lost (Greer 1976, U.S. Army Engineer District, Norfolk 1977a). The constant and often severe erosion of the shoreline prevents permanent vegetation from becoming established. What already is present is eventually washed away as the shoreline recedes (U.S. Army Engineer District, Norfolk undated b). The result is a steady loss of shoreline wildlife habitat and constant turbidity caused by soil being continually washed into the waterway.

Biological impacts of construction and existence of groins, bulkheads, revetments, and large breakwaters are discussed in those sections of this report. Data at hand afford no indication of the possible impacts of sandbag sill placement, but some inferences may be made as to type and degree of probable effects.

Sandbags sills are long polyvinylchloride-coated nylon bags (Dura-bags) filled with sand. Their dimensions are 13 ft (4 m) long, 5 ft (1.5 m) wide, and 2 ft (0.6 m) high. They are placed in the intertidal zone, usually less than 50 ft (15 m) channelward of the mean high waterline. When filled, each bag weighs 4 tons (3.6 metric tons), which is more than waves in the bay can move. Cost is reported as varying from $50 to $150 depending on whether professional help was obtained (Greer 1976).

No data on the construction effects were found. Placing the sill breakwaters amounts to pumping them full of sand and locating them parallel to the eroding shoreline. The area directly beneath each bag would be lost as habitat and the source of sand could cause some depletion elsewhere. Without specific information on construction methods, no further impacts can be predicted.

Once placed, sandbag sills have shown themselves to be very effective in rebuilding beaches in the Chesapeake Bay. In one case a beach was doubled in width in three weeks (Greer 1976). How this local accretion affects adjacent beaches is not stated. The U.S. Army Engineer District, Norfolk (1977e, undated b), predicts no adverse effects due to flood height and drift, reduction of erosion, or accretion on beaches. They also expect no adverse effects on water quality, water supply, or aesthetics. Warning signs are recommended to prevent boaters from hitting the sills, which are submerged at least during high tide.

Prevention of the shoreline erosion should have beneficial effects on the biological resources of the area. Upland vegetation loss would be reduced and, thus, loss of wildlife habitat would be slowed (U.S. Army Engineer District, Norfolk undated b). The effects on intertidal biota would depend, in part, on the amount of sand deposited, and how rapidly deposition occurred. Since erosion and accretion are natural processes, many intertidal organisms can adapt to changing bottom levels. Fish should be little affected except that reduced turbidity might prove beneficial. With no action, erosion might continue. The dredging for beach nourishment is a biologically more harmful alternative, as well as being costly.

Additional information is being developed from ongoing studies at Virginia Institute of Marine Science concerning sandbag sills in Chesapeake Bay.

CASE HISTORY - PIERS, PILINGS, AND OTHER SUPPORT STRUCTURES IN COASTAL REGION 7 - NORTH ATLANTIC

The literature contains very little information on piers and pilings in the Coastal Region 7. Carstea et al. (1975a) present a theoretical case study of a 200-ft (61-m) timber pier in the northeastern United States. A developers' handbook which contains some information on this topic for Connecticut is presented by Carroll (undated).

The construction of a timber pile pier is usually of short duration. For example, Carstea et al. (1975a) estimate construction time of a 50-ft (15-m) long pier at 2 to 4 days, using trucks for 3 hr, a piledriver for 1 hr, and a crane for 10 hr. A slight increase in water turbidity and sedimentation may result. Increased noise and air pollution levels are usually not excessive.

This region is characterized by numerous types of environments (Virginia Institute of Marine Science 1976). Consequently, impacts on the environment due to a specific type of structure will vary from place to place. Effects of a pier on areas such as wetlands, tidal flats, grassbeds, breeding nurseries, wintering and feeding areas, and migration pathways are the most significant (Carstea et al. 1975a). Productivity will be decreased in the area under the pier. This can include vegetation, algal, and shellfish productivity. Grassbeds will also be affected by resultant boat traffic as will the fish activities. Carstea et al. (1975a) recommends that grass beds and other areas of significant natural resource productivity be avoided as sites for pier construction.

Wooden structures in this area should be properly treated against marine wood borer attack, although the problem of attack against treated wood piles should not be as extensive as in some of the warmer coastal waters to the south. The gribble (Limnoria tripunctata), considered to be the species causing the greatest threat to creosote and coal tar treated piles, only breeds where the temperatures are above 57°F (14°C) and is, therefore, not prevalent in Coastal Region 7 (Lindgren 1974).

A single residential pier is not likely to have an extensive impact on recreation in the general area. However, several piers in the area may restrict recreational activities and shoreline access. Pier size and number likewise affect socioeconomics of the area. Piers used in connection with a launching ramp or marina may cause increased usage of the area and affect property values or ecological relationships.

The possible alternatives to a timber pier used for moorage in this area would include solid-fill piers, anchor buoys, single piles, dolphins, placement of boats in local marinas, or land storage. The use of anchor buoys or piles would cause less adverse impact to the environment. The use of a solid-fill pier would, in most cases, be an unsatisfactory alternative due to the influence it would have on water movement and sediment transport.

A single, properly designed and constructed open-pile pier would cause relatively little adverse impact to local biota. Most of the impact would be as a result of related activities, such as dredging or increased usage of the area.

CASE HISTORY - JETTIES IN COASTAL REGION 7 - NORTH ATLANTIC

Except for Long Island, little information on jetties in the New England area was found. The amount of biological data was minimal and was generally applicable to most of the United States coastline (Carstea et al. 1975a).

Fire Island Inlet on Long Island has a documented history extending back to 1825. Fire Island is a long barrier beach lying off the south shore to Long Island. It is broken by a number of inlets, many of which have been stabilized by jetties. The Fire Island Inlet is unusual in that two sections of the barrier beach, Fire Island and Oak Beach, overlap and the inlet curves between them. An irregular channel is maintained by strong tidal currents in the inlet, but throughout its recorded history the channel has maintained its S-shape. Over the years both erosion and accretion has occurred so that Fire Island has grown toward the west and Oak Beach has been cut back (Shepard and Wanless 1971).

A jetty was completed at Democrat Point in 1941. This temporarily stopped the westward advance of Fire Island. The outer beach soon filled behind the jetty on the south side of the island. Following this,sand was deposited landward of the north side and caused a bar to develop. The bar eventually reached nearly across the inlet to Oak Beach. As the channel narrowed, the strength of the tidal currents increased, and severe erosion occurred on Oak Beach. The beach was artificially nourished and a new channel cut, but the latter soon filled. A second jetty was built and erosion has apparently stopped; however,an adequate channel does not exist through the inlet (Shepard and Wanless 1971).

Jetties, as with other shoreline structures which interrupt littoral drift, upset the natural beach processes and cause unwanted and sometimes unforeseen erosion and accretion (Davis et al. 1973). This is well illustrated by the changes in Fire Island Inlet. Not shown were the effects of these changes on the plants and animals of the area. No information was given on habitat loss or alteration. It can be assumed that the construction and existence of the jetties caused impacts on the biological environment. Among the effects of jetty construction at Fire Island Inlet, the following are easily predicted: turbidity, destruction of benthic organisms, reduction of species diversity and food supply, release of toxic sediments, and creation of new substrate (Carstea et al. 1975a). The validity of these predictions could be questioned, however. Additional study would be required to discover site specific impacts.

Jetties are designed to stabilize inlets and, according to Kieslich and Mason (1975), two objectives must be considered. These are minimizing undesirable effects of wave action on navigation channels and eliminating artificial maintenance of the channels. These objectives do not, in any way, consider biological impacts of the jetties. In fact, no source of information was encountered which dealt with the physical or biological impacts of jetties.

CASE HISTORY - BULKHEADS AND ASSOCIATED DREDGING IN COASTAL REGION 8 - GREAT LAKES

In the Great Lakes region (Coastal Region 8) there are a number of references dealing with bulkheads, but very few dealing with associated environmental impacts. Boberschmidt et al. (1976) discussed environmental impact of small structures in the Chicago District of the U.S. Army Corps of Engineers. They provided an analysis of a hypothetical 200-ft (61-m) bulkhead on the Fox River in Wisconsin which involved no dredging. They also considered maintenance dredging at a commercial dock on the Illinois River. Morton (1976) has provided a comprehensive review of the ecological effects of dredging. The U.S. Army Corps of Engineers (undated)gives an excellent layman's introduction to shoreline protection structures for the Great Lakes. Because of a lack of specific information, only generalizations about the effects of bulkheads in the Great Lakes are contained in this case history study.

Bulkheads are constructed in the Coastal Region 8 to retain, or prevent the sliding of, land and secondarily to protect the upland against wave damage. Bulkheads also provide mooring facilities in many areas. Many unsatisfactory methods of shoreline protection may be employed prior to installation of an adequate structure such as a bulkhead (U.S. Army Corps of Engineers undated).

Many possible construction alternatives exist. They vary substantially in cost. A wire mesh, woodpile, or sandbag bulkhead may cost no more than $15 per linear foot (0.3 m), while a steel bulkhead may cost as much as $330 per linear foot (0.3 m) (U.S. Army Corps of Engineers undated). Among the construction alternatives which may be considered in addition to many types of bulkheads are revetments, breakwaters, and groins.

Construction impacts of bulkheads are similar to those in other areas of the country, including increased turbidity and noise, reduced air quality, and smothering of some organisms in the backfill area. Resuspension of bottom sediments will be greater when dredging is associated with bulkhead construction. The use of diked disposal for hydraulic dredge spoils results in significantly less turbidity than many other methods of disposal (Morton 1976).

Bulkheads and seawalls are often successful in providing immediate protection for areas in which no further bluff recession can be tolerated, but they frequently fail because of toe erosion and back pressure (Michigan Sea Grant Advisory Program undated). Forney and Lynde (1951) document a history of attempts to protect the Presque Isle peninsula from erosion.

The effects of bulkheads on coastal processes are similar to those found in other coastal regions. Erosion in adjacent areas which are not bulkheaded or otherwise protected can sometimes be expected. Littoral transport may also be affected. A lack of dissipation of wave energy can be expected on the lakeshore during storms as compared to the unbulkheaded beach (Boberschmidt et al. 1976).

Biological impacts resulting from the presence of a bulkhead include some reduction in littoral zone productivity. Foreshore habitat is likely to be eliminated by construction of a bulkhead. In rivers,bulkhead construction reduces cover along the banks (Boberschmidt et al. 1976). Dredging may cause increases in suspended solids, reduction in dissolved oxygen and increased concentration of hydrogen sulfide, and release of pollutants which may be trapped in the sediments (Morton 1976). These factors can be detrimental to fish and other organisms in the vicinity of the dredging operation.

Bulkheading may protect certain areas from erosion, at least temporarily. Bulkheads may also provide mooring facilities. However, recreational activities requiring unaltered habitat will be restricted by bulkhead construction.

Because bulkheads may result in an increased energy environment and erosion of adjacent beach areas, riprap revetments may be preferred as an alternative. If the bulkhead is needed, riprap revetment may be placed in front of the bulkhead to reduce scour and biological damages. Exchange of subsurface water is facilitated through riprap; wave energy is somewhat reduced because of its increased roughness. Both revetments and bulkheads may limit access to beaches. Groins and breakwaters can also be considered as alternatives to preserve a beach by altering shoreline processes.

CASE HISTORY - GROINS IN COASTAL REGION 8 - GREAT LAKES

The Michigan Demonstration Erosion Control Program is involved in an ongoing research program to test the effectiveness of various shore protection devices. The physical environment at each test site is known; but, unfortunately, no information is collected concerning the biological environment. The other sources of information concerned with groins in the Great Lakes do not include biological impact data either. Biological effects must be inferred from general information.

Four Mile Park on the Lake Huron shore in Sanilac County, Michigan, was chosen as a test site for the six groin types (Table 3). The bottom is clay derived from the high clay bluffs along the shore. Erosion has long been a problem and homes have been destroyed as the bluffs eroded (Brater et al. 1974). All six groins have had some success in trapping sand at the base of the bluffs (Figures 56 to 59); however, the bluff is continuing to recede (Brater et al. 1977).

No information on construction impacts was given. However, they can be assumed to vary from mild turbidity and beach disturbance for the sandbags to somewhat more turbidity and beach disturbance plus air and water pollution for rock mastic structure. These were constructed by pushing the rocks previously dumped on the beach into place with bladed tractors and pouring hot asphalt mastic over them (Brater et al. 1974). The effects of construction activities on the biota is not known. Since the shoreline was actively eroding, with little or no beach, any organisms present should be adapted to a disturbed environment.

The success of the groins in trapping sand resulted in a change from a clay to a sand substrate. This may have resulted in a change in species composition of bottom dwelling organisms. When a beach accumulates enough sediment to prevent storm waves from striking the bluffs and continuing the erosion, loss of upland vegetation and man-made structures along the bluff should stop.

Table 3. Groin types and their performances,
Sanilac County, Michigan (Brater et al. 1974, 1975, 1977).

Groin type	Year placed	Cost/ft of groin	Construction problems	Performance evaluation 1974	Performance evaluation 1975
3 Longard tubes, 40-in (102-cm) stacked	1973	$ 55	Installation interrupted by storms, top tube not placed	Intact, no maintenance; sand trapped but bank receded	Intact, no maintenance; sand trapped but bluff still recedes
Longard tube, 69-in (175-cm)	1974	$ 71	None	Intact, no maintenance, some bank recession, no more successful than 40-in (102-cm) tubes	Intact, no maintenance; sand trapped and only minor bluff recession
Sandbags	1973	$109	None	Sand bags lost, torn; sand trapped	Not durable but offers good temporary protection
Rock mastic	1973	$154	Difficulty obtaining proper rock	Intact, no maintenance; sand trapped	Minor damage, no maintenance; not attractive
Gabion	1974	$ 30	None stated	Too early to evaluate	
Timber crib	1975	$ 30	Difficulties getting it built	Not installed	Too early to evaluate

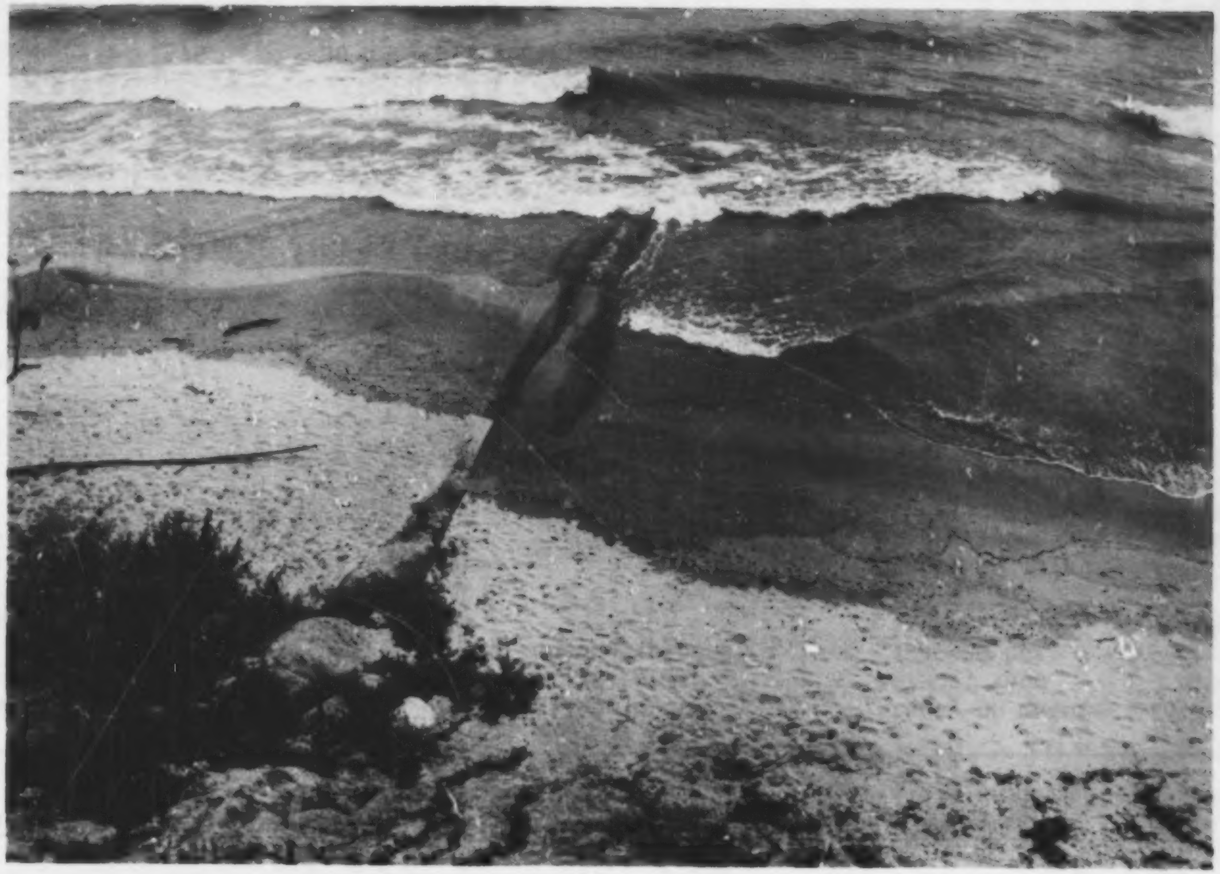

Figure 56. A 40-in (1-m) Longard tube groin at Sanilac site. Photograph courtesy Michigan Department of Natural Resources.

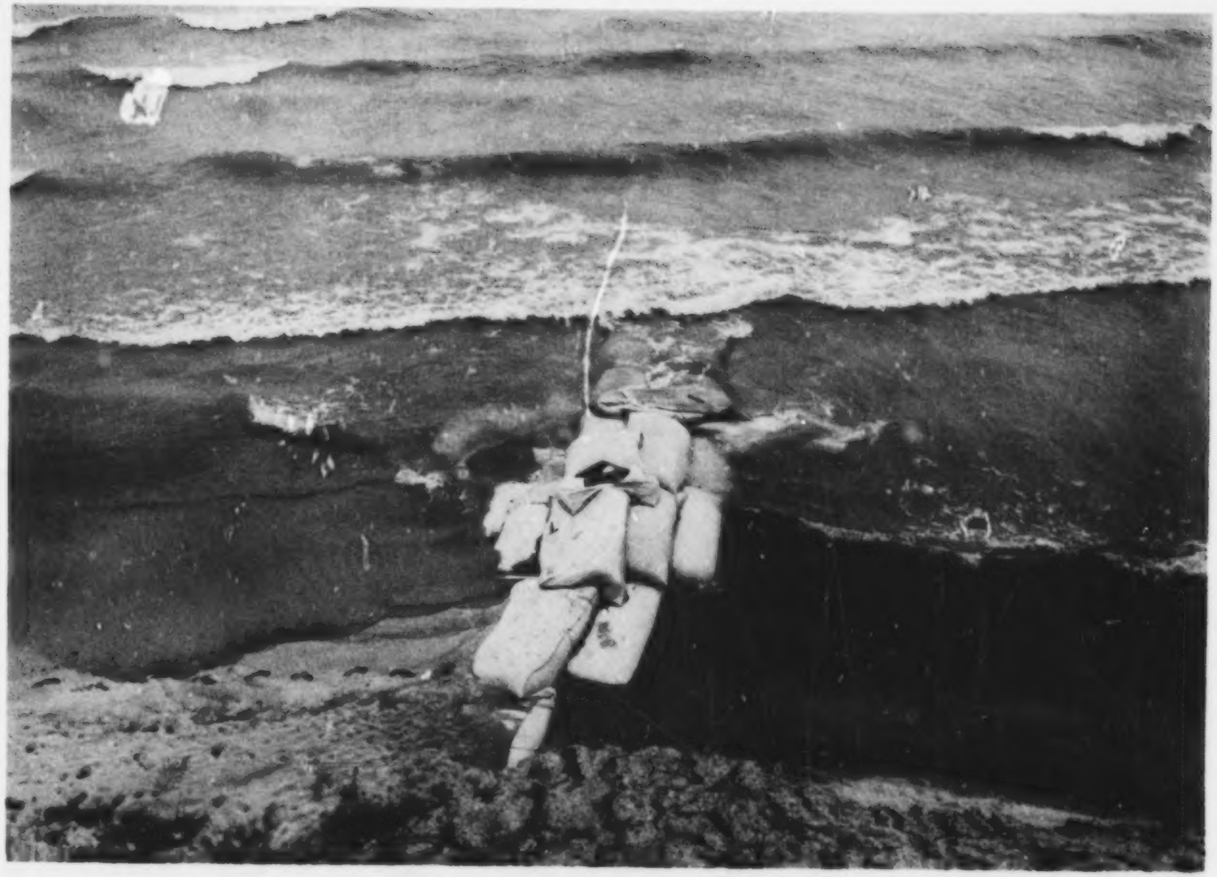

Figure 57 . Sandbag groin at Sanilac site, showing loss of sandbags at lake end. Photography courtesy of Michigan Department of Natural Resources.

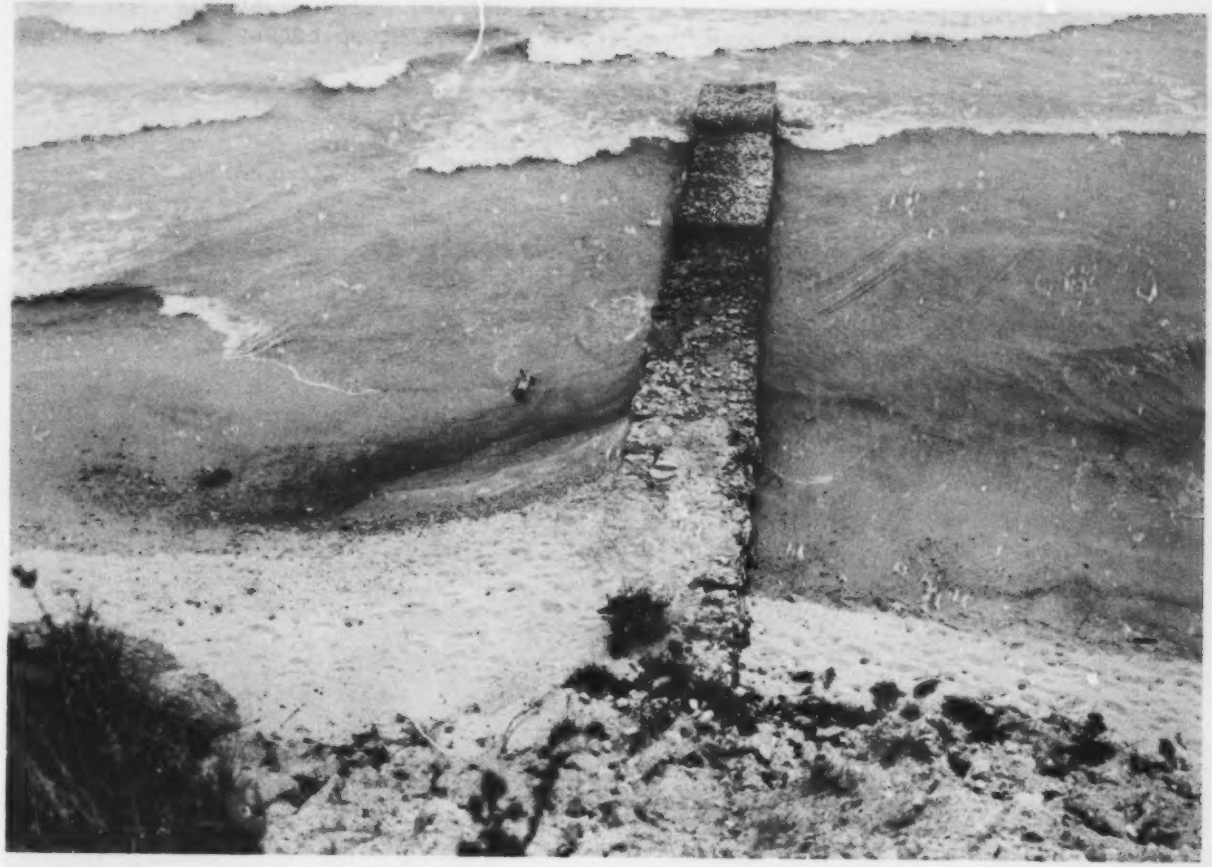

Figure 58. Gabion groin at Sanilac site. Photograph courtesy of Michigan Department of Natural Resources.

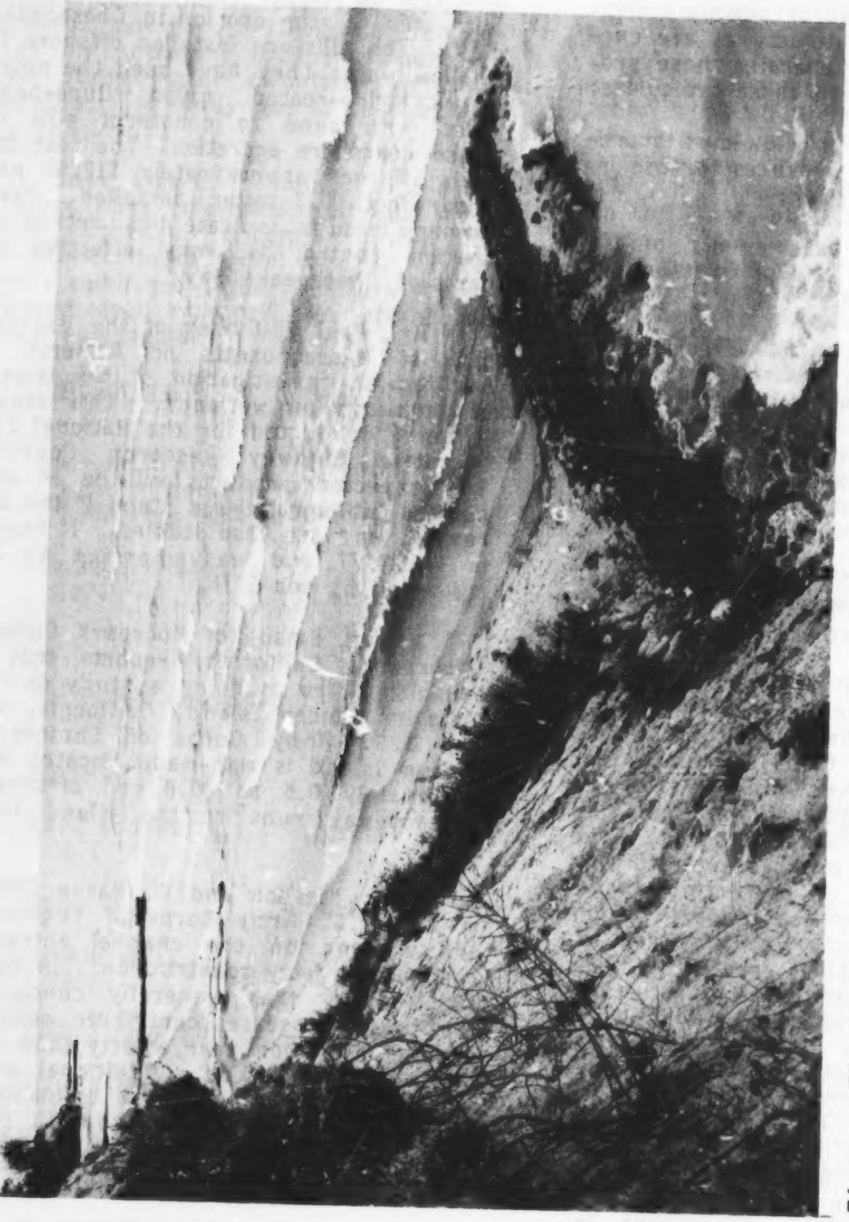

Figure 59. Rock mastic groin at Sanilac site. Photograph courtesy of Michigan Department of Natural Resources.

RESEARCH IN PROGRESS

Seven research projects investigating the design of and/or biology associated with shoreline structures are currently underway. Generally these projects can be placed in three categories:

- o Those looking for low-cost shoreline protection measures for use by the property owner;
- o State of the art reviews of the structure type and/or its effect on the environment;
- o Research about the effects of a structure type on either the biological or physical environment.

Projects investigating various low-cost protection measures, such as the Michigan Demonstration Erosion Control Program, often include construction of a structure as well as identification of the problems. The other two types of research usually concentrate on effects of existing shoreline structures.

The Michigan Demonstration Erosion Control Program, initially funded by the Michigan Department of Natural Resources, began in 1973. Since that time, it has received funding from the several other organizations, including the Michigan Sea Grant Program. The objective of this program was to find low-cost methods of protecting Michigan's shoreline which a property owner could help construct. Low cost was defined as under $100 (preferably less than $50) per square foot of protection. Nineteen shore protection demonstration installations have been constructed. These include revetments, breakwaters, bulkheads, and groins. Laboratory investigations and historical studies of erosion conditions are also being constructed. It is hoped that by 1978 enough information will be available to evaluate the effectiveness of each installation. A detailed engineering-economic evaluation of the structures will be made. Reports are published each year discussing data collected during the previous year.

Greer (1976) reported that Robert Byrne and Gary Anderson of Virginia Institute of Marine Science are working with sills to stop erosion in Chesapeake Bay. The sills are installed offshore in shallow water.They have used the polyvinylchloride-coated nylon Dura-bags filled with sand to construct sills to cause nearshore accretion. The cost for each sill was approximately $12.50 per linear foot (0.3 meter) installed. Preliminary results indicate this method of erosion control is very effective in parts of Chesapeake Bay.

Dr. Paul Shuldiner of the University of Massachusetts at Amherst is heading an investigation of the impact of highways on wetlands. This study is being conducted for the National Cooperative Highway Research Council. The expected products will be an annotated bibliography, a state of the art review, and six case studies. It began in mid-1977 and was expected to be completed by mid-1978.

William Brisby of Moorpark College (Moorpark, California) reports that a consulting firm is doing a study on the biota of Rincon Island, California, for the U.S. Army Corps of Engineers. Rincon Island is man-made, located approximately 0.5 mi (0.8 km) offshore. A causeway runs to the island from shore.

J.M. Kieslich and C. Mason (1976) of the U.S. Army Corps of Engineers are working on the channel entrance response to jetty construction. In their 1975 paper, they generally concluded that wave processes contribute more to channel migration near a jetty than hydraulic processes do. Additional work is being performed by them to quantify the controlling wave and hydraulic processes. Their results will be presented in a future report.

Two studies are underway at the University of Rhode Island at Narragansett. Neil Ross and Gail Chmurg are conducting a state of the art review of the biological impacts of small boat harbors. Daniel O'Neil is investigating the fouling communities on the floating tire breakwaters for the Marine Advisory Service. The objectives of O'Neil's study are to identify and quantify fouling communities, determine rates of growth, look for the biological mechanisms of controlling fouling communities, and study water circulation in small harbors. The study was to be completed by Fall 1977.

Some articles contained in the literature make reference to studies which were planned or underway at the time of publication of those articles. References published prior to 1975 which indicated that research was planned or underway included

Researcher	Structures to be Studied
Georgia Department of Natural Resources 1974	groin
Marks and Clinton 1974	revetments, breakwaters, bulkheads, and groins
Machemehl and Abad 1973	groin
Stone et al. 1973	reef
Berg and Watts 1971	groin
Riese 1971	groin
Cronin et al. 1969	dredge-fill, jetty, groin
Colley 1967	pilings
Slaughter 1967	bulkhead
Saville et al. 1965	revetment
Lee 1964	harbors
Scott 1964	jetty
Nagai 1961	breakwater
Brater 1954	bulkhead, revetment, groin
Cole undated	breakwater, harbor

The only results of these proposed studies which were uncovered during the present study are contained in the articles by Brater et al. (1974, 1975, 1977). These studies were alluded to in the Marks and Clinton (1974) article.

It is presumed that there are many relevant studies underway that are not noted in the literature or that were not determined during interviews or in responses to questionnaires. In addition, there are most likely numerous studies underway that deal with strictly engineering aspects of shoreline structures. The best sources of information regarding ongoing studies are probably the U.S. Army Engineer Coastal Engineering Research Center in Fort Belvoir, Virginia, and the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi.

A large number of studies which are somewhat peripheral to the present study are also presently underway. Examples would be the numerous biological studies on artificial reefs and dredging effects and engineering studies on materials, life expectancy, and structure design.

ENVIRONMENTAL IMPACT ASSESSMENT METHODOLOGY

The majority of studies assessing the environmental impact of minor shoreline structures on the coastal environment have been nonexperimental. Over 75% of the information sources reviewed were literature reviews, guidelines, and nonexperimental environmental impact assessments and statements.

Systematic research studies conducted before and after the structure installation were rare, and those conducted were almost exclusively concerned with physical effects or engineering considerations. One ongoing research program that falls into this category is Michigan Demonstration Erosion Control

Program (Brater et al. 1974, 1975, 1977; Marks and Clinton 1974). This study is limited primarily to physical effectiveness of low cost groins and revetments. In another study, historical records were compared with the existing conditions to discover changes in littoral drift and the beach erosion after a jetty was constructed (Dantin et al. 1974). One series of biological studies was conducted both prior to and after installation of various parts of a marina in southern California (e.g., Reish 1961, 1962, 1963).

Another research method involves systematic studies conducted after the installation of structures. These studies primarily described the physical conditions in the presence of a structure. For instance, Diskin et al. (1970) described piling up of water behind low and submerged breakwaters, and Nagai (1961) discussed the absorption of wave energy by concrete facing components. An exception to this generalization has been a number of biological studies which have compared the existing bulkheaded areas to adjacent natural shorelines. Examples of this method of study are found in Corliss and Trent (1971), Ellifrit et al. (1972), Heiser and Finn (1970), Millikan et al. (1974), Mock (1966), Moore and Trent (1971), Trent et al. (1976), and White (1975).

EVALUATION OF EXISTING DATA

INFORMATION OBTAINED

555 references were obtained that were considered potentially applicable to the objectives of the study. Numerous additional articles were uncovered, but not obtained because they were not applicable. The 555 articles were considered as potentially applicable, based on their title or on recommendations contained in the questionnaires or acquired during interviews. These articles were read and abstracted, and data sheets prepared where appropriate. An article was assigned a rating only if it was directly applicable to the present study. About 405 of the articles that were read were considered directly applicable. The remaining 150 articles contained information that was related, but not directly applicable to the study.

Figure 60 contains histograms of the number of references obtained by structure, category, and rating. It is emphasized that the rating was for usefulness to the present study and not scientific excellence or validity. Information of questionable validity is of questionable usefulness, but information of high veracity may also be of limited usefulness.

The consensus of personnel who worked on this study was that structures could be classified as having the high, moderate, or low potential for environmental impact as follows:

High impact potential

- Small boat harbors
- Bridges and causeways
- Bulkheads
- Breakwaters
- Jetties

Moderate impact potential

- Revetments
- Groins
- Ramps

Low impact potential

- Buoys and floating platforms
- Piers, pilings, and other support structures

Based on this classification and the histograms in Figure 60, bridges and causeways, and the small boat harbors would appear to have received a small amount of study in light of their potential impacts. It should be noted, however, that the data base contains much information that is not impact assessment oriented, but directed at engineering constraints.

Figure 61 contains the number of references obtained by structure type and coastal region. The general category is for articles that were not specific for one coastal region. Much of the acquired information was not region specific. In many cases the histograms reflect structure prevalence and history of associated difficulties within that region. Examples would be jetties in the North Pacific (Coastal Region 1) and bridges and causeways in South Florida (Coastal Region 4). This is not always the case, however, as is exemplified by the small boat harbors in South Florida (Coastal Region 4).

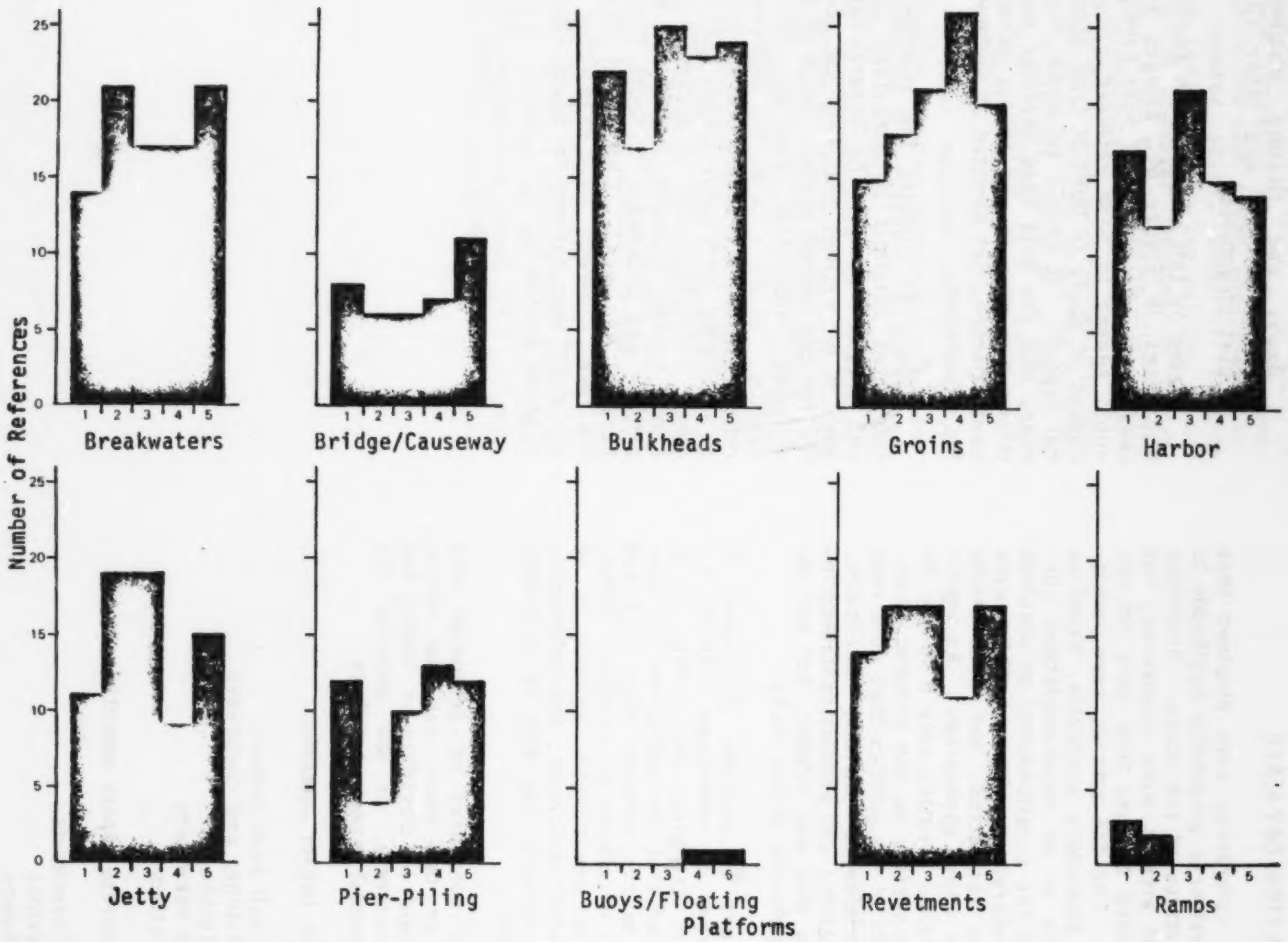

Figure 60. The number of references by structure category and rating that contained information relevant to the present study. A rating of 1 indicated the articles that were most useful.

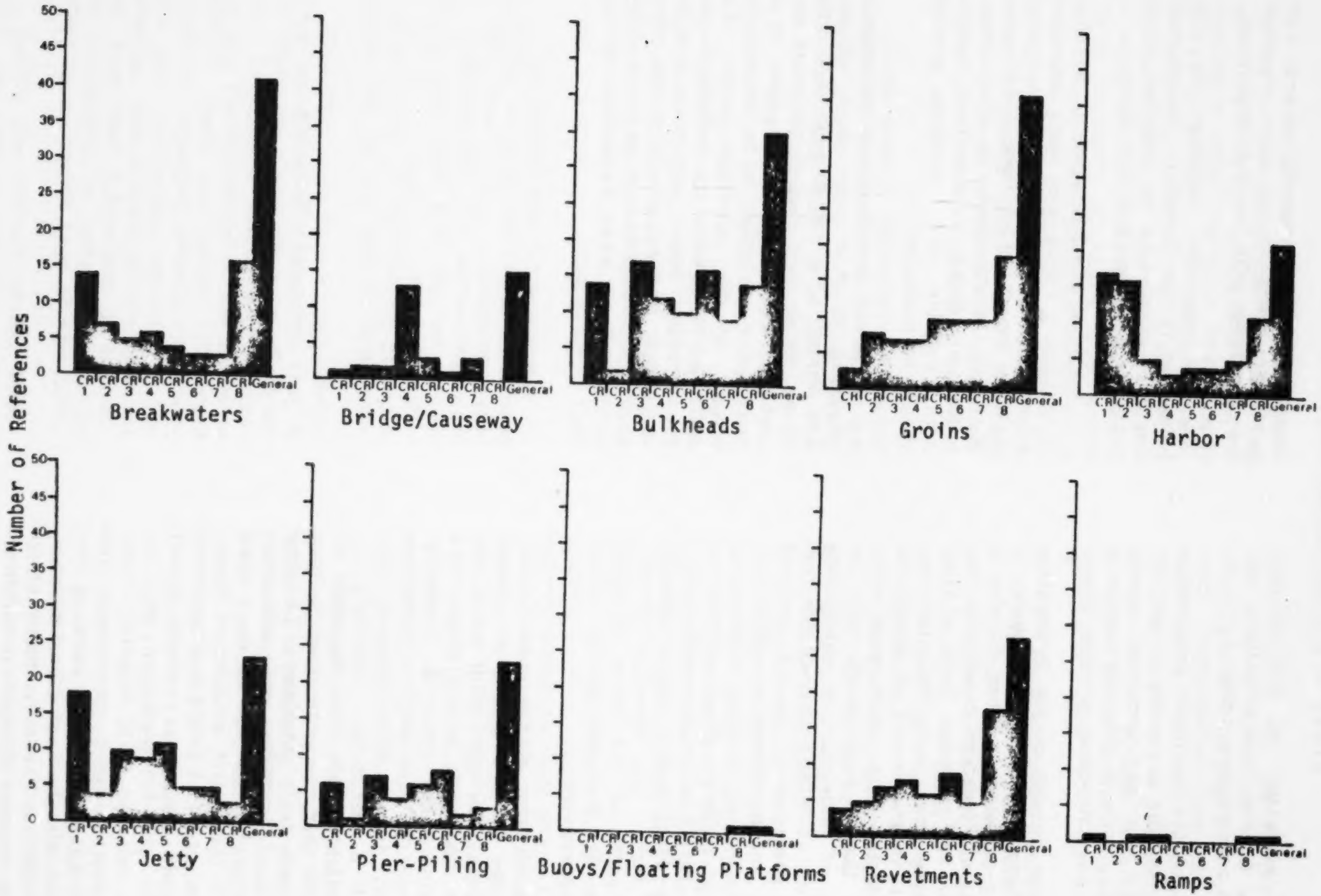

Figure 61. The number of references by coastal region and structure that contained information that was relevant to the present study. The general category is for references that were not specific to one region.

GENERAL COMMENTS ON THE DATA BASE

After evaluation of the existing data base, several generalizations can be made as constructive criticism.

Much of the available information was developed for a specific project as support for an environmental impact assessment. Some of this information is biased in one direction or the other.

A large amount of the information on the effects of shoreline structures is engineering-oriented. There is also a large body of literature concerning the distribution and tolerance limits of biota of the coastal zone. Very little information exists on the impact of structures upon the biota. As a result, most environmental impact assessments rely on the ability of individuals to extrapolate impacts from what they know of the construction procedures, coastal physical processes, and nonstructure related biological data. Most of these assessments are made in a climate of potential litigation. The result is an extremely watered-down product that is only marginally based on fact. The literature on biological impacts of the minor shoreline structures is characterized by these types of assessments.

An evaluation of the potential impact of some minor shoreline structures by a competent biologist often would result in a negligible impact conclusion. Unfortunately, the present regulatory climate necessitates a lengthy discussion of potential impacts. In order to prepare such a discussion, seemingly inconsequential matters are discussed at such length that everyone starts believing they are truly problems. Lengthy discourses of turbidity and sedimentation effects of rocks landing on a sand bottom fill the impact assessment literature. It is doubtful that competent biologists would project a probable impact due to fish gills being clogged, fish dying from released toxic materials, benthic organisms being smothered, and primary productivity being reduced simply by the placement of stone in intertidal habitats. However, these statements are rampant throughout the literature, with the sideline comment that these impacts are probably minor. This syndrome seems to be more prevalent for structures with low potential impact.

The opposite syndrome is also evidenced in the literature. An example would be concluding no potential impact based on a nonexistent data base.

Much of the literature is negative in nature. There are many examples where structures have had an overall positive impact on an area. Attraction of fishes to structures is often interpreted as being a beneficial impact. Both positive and negative aspects should be evaluated.

Much of the literature evaluates a structure as if it were in a vacuum. The impact of a single groin will often be negligible, but that single groin may cause a stepwise series of groins to be built, each of which is to mitigate the effects of the previous groin. The socioimpacts caused by bulkheads and the resultant house, or ramps and the associated boating pressure are other examples. Factors such as these should be considered when evaluating the impact of structures.

RESEARCH NEEDS

A detailed review of the literature results in the conclusion that the data base available for projecting biological impacts of minor shoreline structures is extremely sparse. The research needs are virtually unlimited for each type of structure and for each coastal region. It would be unreasonable to propose a study on each structure type within each coastal region that was designed to determine the magnitude of each conceivable type of impact. We have, therefore, proposed avenues of approach that will result in timely and cost-effective answers to the questions most frequently asked.

Data used in determining biological impacts of the shoreline structures are usually drawn from three data bases. The most applicable data base is the one containing information on the chemical, biological, or physical impact of a specific type of structure. Examples would be articles on chemical releases from resuspended sediments during the jetty construction, fish attraction to breakwaters, and changes in beach profile due to groins. As is evident in the text of this report, this type of information is scarce.

The second data base contains information on engineering considerations in structure design. Examples would be methodologies for calculating wave impact, structural integrity, or changes in littoral transport. This information is often useful in determining biological impact, but is not directly applicable.

The third data base contains information on biological phenomena that is not related to a specific type of structure. Examples of this type of information are the attraction of the fishes to artificial reefs and other submerged structures; dredging effects upon benthos; and succession, diversity, productivity, and biomass of the communities that foul submerged structures. This information is useful if it can be applied to a specific type of structure.

During the present study, information was entered into the data base only when it was specific for a particular type of structure and a physical, chemical, or biological environmental impact. Information from the other two data bases was not entered into the system. During the present study, descriptions of certain impacts recurred through the literature. Examples of the more significant recurrent impacts are

- Changes shoreline dynamics
- Affects littoral transport
- Changes wave energy
- Changes sediment composition
- Increases turbidity
- Causes suspension of toxic chemicals
- Changes dissolved oxygen, salinity, or temperature
- Shades the water
- Affects circulation
- Alters existing habitat or creates new habitat
- Alters species composition
- Affects migration patterns
- Socioeconomic changes due to increased area usage

A study should be performed to analyze each of the recurrent types of impacts based on each of the three data bases. For example, the effects of increased turbidity due to any of the structures would be a valuable study. An impact approach in addition to a structural approach would result in a considerable refinement of the conclusions reached in this report.

Review of available literature uncovered certain major gaps in the data base. The following recommended studies would help to fill in some of these areas where information is lacking.

- How are biological communities affected by structures which stabilize shorelines?

- How do changes in wave energy patterns affect biological communities? For example, what are the differences in communities in front of and behind breakwaters?

- What are the positive and negative effects of changing the type of habitat that occurs in the area (e.g., rock vs sand)?

- Does construction-generated turbidity clog fishes' gills or zooplankton/filtration mechanisms. Do avoidance mechanisms operate to prevent this?

- Can loss of phytoplankton or macrophyte primary productivity due to structure shading constitute a threat to an ecosystem?

- Can loss of phytoplankton or macrophyte primary productivity due to construction turbidity constitute a threat to an ecosystem?

- What are the effects of structures that protrude into the water or channelize current upon the migration of fishes, mammals, and crustaceans?

- How do solid structures affect systems through alteration of circulation?

- What are the biological effects of structures such as rubble mound groins or riprap revetments in areas where this type of habitat did not formerly exist?

- Under natural conditions, is available habitat one of the most important factors controlling the productivity of a specific organism?

- What are the effects of altered wave energy patterns upon sediment composition and associated biological productivity?

- What are the zones of influence of wave energy altering structures? For example, how far away from a bulkhead are the energy alterations felt? Bottom profile and sediment composition alterations are included in this concern.

- What are the effects of various types of submerged surfaces on productivity? For example, does a riprap revetment offer a better habitat than a bulkhead or concrete revetment?

- What are the cumulative effects of many of the same type of structure in an area or a combination of many types of structures in an area? Studies similar to those on bulkheading in Texas (Coastal Region 3) are needed in the other coastal regions and about other types of structures.

- What are the effects of shoreline structures on waterfowl and other wildlife?

Answers to all the above questions could be generated through field or laboratory studies. There are certain questions, however, that could best be answered through a literature review which incorporates all three of the aforementioned data bases. The results of the literature review could answer the questions or could serve as a firm basis on which to design the required field or laboratory studies.

The case history studies for each coastal region were selected based on the recommendations of local U.S. Fish and Wildlife Service personnel. Their recommendations were based on the most troublesome structures they encounter when reviewing Corps of Engineers' permit applications. In several cases, there was not enough information available to write a case history, and theoretical case histories were constructed. In other instances, the data base was so poor that the majority of the case histories was theoretical. Circumstances where theoretical information was used would seem to be appropriate topics for detailed study. These topics were

Southern California
Coastal Region 2
Bulkheads

South Atlantic
Coastal Region 5
Groins

South Atlantic
Coastal Region 5
Bulkheads

North Atlantic
Coastal Region 7
Piers, piling, and other support structures

North Atlantic
Coastal Region 7
Jetties

Great Lakes
Coastal Region 8
Bulkheads and associated dredging

Great Lakes
Coastal Region 8
Groins (biological)

It was the consensus of project personnel that small boat harbors had a high potential for environmental impact. Small boat harbors can contain all of the other structures mentioned in this report. Harbors would, therefore, make good case studies within each region of the United States. The effects of numerous structures could be studied at one location and within the budgetary constraints of one study. Sites will have to be carefully chosen, however, to assure that the effects of one structure type are not overpowering the effects of another or that secondary effects, such as petrochemical pollution, are not of far greater significance than the strictly structural effects.

Project personnel also considered bridges and causeways to have a high potential for environmental impact. Unlike many other structures, their effect can extend over an area much larger than the immediate vicinity where they are constructed. Such regional impacts are discussed in the case history studies on bridges and causeways in Florida (Coastal Regions 3 and 4). Detailed studies on the effects of bridges and causeways would help to determine if fears, arising largely from conjecture, are factually based. It would be very helpful if several locations could be studied both before and after construction. The effects on tidal circulation, biological productivity, and flood control should be prime concerns of the study.

In summary, there are numerous studies that would enhance the state of the art relative to the prediction of the biological impacts of minor shoreline structures on the coastal environment. One avenue of approach that will result in timely and cost-effective answers to many structure-related questions is the integration of the purely biological, purely engineering, and structure impact related data bases currently in existence. In addition to this approach, there are several field studies which, if undertaken, would contribute substantially to the presently available data base.

GLOSSARY[1]

Aerobic
Life processes occurring only in the presence of free oxygen.

Anaerobic
Life processes occurring without the presence of free oxygen.

Anadromous
Fish that reproduce in fresh water, but spend a portion of their life in salt water.

Backfill
Material used to fill behind a small structure such as a seawall or bulkhead.

Backshore
Zone of beach lying between foreshore and coastline acted upon by waves only during severe storms.

Barrier beach (also barrier island)
Bar essentially parallel to shore, with crest above normal high water.

Bay
Recess in shore or inlet between two capes or headlands; larger than cove, smaller than gulf.

Baymouth bar
Bar across the mouth of an embayment.

Benthos
Organisms growing on or associated principally with the water bottom.

Berm
Nearly horizontal part of beach or backshore formed of material deposited by wave action.

Biota
Animal and plant life of a region.

Biotic
Environmental factors which are the result of living organisms and their activities.

Bluff
High steep bank or cliff.

Boat basin
Naturally or artifically enclosed or nearly enclosed harbor area for small craft; see *harbor*.

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[1] Portions of this glossary have been estracted or adapted from Allen (1972) and Hurme (1974).

Boulder
Rounded rock more than 10 in (25.4 cm) diameter; larger than cobblestone.

Breaker zone
Zone of shoreline where waves break.

Breakwater
Structure protecting shore area, harbor, anchorage, or basin from waves; see *jetty*.

Bridge
Structure erected to span natural or artificial obstacles such as rivers, highways, or railroads and supporting a footpath or roadway for pedestrian, highway, or railroad traffic. A bridge would normally consist of structural members made of steel, concrete, or wood.

Bridge abutment
Structure supporting the bridge at the point where the land meets the water as distinguished from a pier which is wholly in the water.

Bridge pier
Structure in the water which supports a bridge.

Bulkhead
Structure or partition built to prevent sliding of the land behind it. It is normally vertical or consists of a series of vertical sections stepped back from the water. A bulkhead is ordinarily built parallel or nearly parallel to the shoreline.

Buoy
A floating object moored to the bottom of a waterway, used for marking, moorage, etc.

Caisson
A watertight structure used for construction work in water.

Calcareous
Consisting of or containing calcium carbonate.

Canal
Artificial watercourse cut through land area.

Cape
Relatively extensive land area jutting seaward from continent or large island which prominently marks change or interruption of coastal trend.

Causeway
A way of access, or raised road, typically across marshland or water. A causeway would normally consist of an embankment constructed of earth, sand or rock dredged or dumped in place.

Cliff
High steep face of rock.

Climax
Final and most stable of series of communities in succession, remaining relatively unchanged as long as climatic and physiographic factors remain constant.

Cobble
Naturally rounded rock, 3 to 10in diameter.

Cofferdam
A temporary watertight structure built in the water and pumped dry for construction of piers, bridges, dams, etc.

Community
Association of plants and/or animals in given area or region in which various species are more or less dependent upon each other.

Coquina
A soft porous limestone with high shell and coral content.

Cove
Small, sheltered recess in coast, often inside larger embayment.

Cumulative effects
Effects which result from an accumulation of a number of structures in a coastal area.

Current, long shore
Littoral current in the breaker zone moving parallel to the shore.

Deadman
A wooden pile, concrete block or horizontal timber placed landward of a bulkhead and used to anchor the structure; (see Figure 27).

Delta
Alluvial deposit, triangular or digitate, formed at river mouth.

Design wave height
Wave which is used for designing coastal structures such as revetments, breakwaters, jetties, or groins. The wave height and period assists the designer in selecting sizes of armor units and other features of the structure. The design wave will probably not be the maximum wave for economic reasons.

Detached breakwaters
Breakwaters standing free of the shore; see *breakwater.*

Dike
Wall or mound built around low-lying area to control flooding.

Disclimax
Plant community in which species composition is maintained by continuing disturbance.

Dock

Place for loading and unloading of vessels/for small boats; see *pier*.

Dolos, dolosses (plural)

A type of precast concrete armor unit used for facing rubble mound structures.

Dolphin

Cluster of piles; see *piling* , also Figure 43.

Dredge

To deepen by removing substrate material; also, mechanical or hydraulic equipment used for excavation.

Ebb tide

Period between high water and the succeeding low water; falling tide.

EIA

Environmental impact assessment (or analysis); the analysis of the potential impact of a proposed development project upon its immediate and more distant environment.

EIS

Environmental impact statement; the actual presentation that results from the *EIA*.

Embankment

Artificial bank such as a mound or dike, generally built to hold back water or to carry a roadway.

Embayment

Indentation in shoreline forming open bay.

Endemic

Peculiar to particular region or locality; native.

Erosion

Wearing away of land by natural forces; e.g., by wave action, tidal currents, littoral currents, deflation.

Estuary

Region near river mouth where fresh river water mixes with salt water of sea.

Fetch

The distance over unobstructed open water on which waves are generated by a wind having a constant direction and speed.

Filter

Transitional layer of gravel, small stone, or fabric between fine material of an embankment and revetment armor.

Float
Floating platform or other device moored to bottom of a waterway.

Flood tide
Period between low water and the succeeding high water; rising tide.

Food chain
Dependence of a series of organisms, one upon another, for food; begins with plants and ends with largest carnivores.

Forb
Herb other than grass.

Foreshore
Part of the shore lying between crest of seaward berm and ordinary low water mark.

Freeboard
Distance between waterline and top deck of a structure or vessel.

Fringe marsh
A narrow wetland at the edge of a body of water.

Gabion
Hollow cylinder filled with earth; see *revetment*.

Grass flats
Flat areas alternately covered and uncovered by tidal action which support extensive growths of grasslike vegetation.

Gravel
Loose, rounded fragments of rock, 0.75 to 3in (1.8 to 7.6cm) diameter.

Groin, groyne (Bristish)
A rigid structure built at an angle (usually perpendicular) from the shore to protect it from erosion or to trap sand. A groin may be further defined as permeable or impermeable depending on whether or not it is designed to pass sand through it.

Groin field (also groin system)
Series of groins spaced along the shoreline acting together to protect a section of beach.

Gribbles
Small marine isopod crustacean (Limnoria spp.) that destroys submerged timber.

Gulf
Large embayment, entrance generally wider than length.

Habit
Characteristic mode of growth or appearance.

Habitat
Interacting physical and biological factors which provide at least minimal conditions for one organism to live or for a group of organisms to occur together.

Habitat type
All the area that presently supports a community or organisms.

Harbor
Any protected water area affording place of safety for vessels; for the purposes of this study, includes boat basins, marinas, and moorage.

Headland
High steep-faced promontory extending into sea.

Herb
Seed-producing vascular plant that produces no woody tissue and dies back at end of growing season.

Hook
Spit or narrow cape of sand or gravel which turns landward at outer end.

Impact
An action producing a significant causal effect or the whole or part of a given phenomenon.

Impermeable groin
Groin through which sand cannot pass; see *groin*.

Individual lot pier
One-owner pier usually serving single property.

Inlet
Water passage to an inland water; or a recess in the shore such as a bay.

Internation Great Lakes tidal datum (IGLD)
See *tidal datum*.

Invertebrate
Animal lacking an internal skeletal structure, e.g., insects, mollusks, crayfish, etc.

Isthmus
Narrow strip of land, bordered on both sides by water, connecting two larger bodies of land.

Jet
To place in ground by means of jet of water acting at lower end.

Jetty
Structure extending into body of water designed to prevent shoaling of channel by littoral materials and to direct or confine stream or tidal flow; see *breakwater*.

Key (also cay)
Low insular bank of sand, coral, etc.

Lagoon
Shallow body of water, usually connected to sea.

Levee
Usually manmade dike or embankment to protect land from inundation.

Life cycle (life stage)
The various phases or changes through which an individual passes in its development from the fertilized egg to the mature organism.

Lightering buoy
Point buoy; tie up for a small craft; see *buoys and floats*.

Littoral
Of or pertaining to a shore.

Littoral drift
Sedimentary material in littoral zone under influence of waves and currents.

Littoral transport
Movement of littoral drift by waves and currents; includes movement parallel to and perpendicular to shore.

Marina
Small harbor or boat basin providing dockage, supplies, and services for small pleasure craft, see *harbor*.

Marine way (also marine railway, launchway)
Railway extending into water used to launch or to pull vessels from water; see *ramp*.

Mean high water
Average height of high waters over a 19-yr period (MHW).

Mean low water
Average height of low waters over a 19-yr period (MHW).

Mean sea level
Average height of surface of sea for all stages of tide over 19-yr period (MSL).

Mean tide level
Plane midway between mean high water and mean low water (also half-tide level).

Migration
Mass movement of animals to and from feeding, reproduction, or nesting areas.

Mole
Massive land-connected, solid-fill structure of earth (generally revetted) masonry or large stone; see *jetty*.

Monolithic
Type of construction in which structure's component parts are bound together to act as one.

Moorage
Place to make a vessel fast with anchors, cables, etc.; see *harbor*.

Mud
Fluid-to-plastic mixture of finely divided particles of solid material and water.

Mud flats
Low, unvegetated mud substrate that is flooded at high tide and uncovered at low tide.

Neap tide
Tide occurring near time of quadrature of moon with sun, usually with range 10% to 30% less than mean tidal range.

Nekton
Macroscopic organisms swimming actively in water; e.g., fish.

Neritic zone
Relatively shallow water zone which extends from the high-tide mark to edge of continental shelf.

Nesting
Pertaining to brooding eggs or rearing young.

Nourishment
Process of replenishing a beach; naturally by longshore transport or artificially by deposition of dredged material.

Nursery
Area where young are born or cared for.

Nutrients
Elements or compounds essential as raw material for organism growth and development; e.g., carbon, phosphorous, oxygen, nitrogen.

Outfall
Structure extending into a body of water for the purpose of discharging an effluent (sewage, storm runoff, cooling water).

Parapet
Low wall built along edge of a structure.

Pass

Navigable channel through bar, reef, shoal, or between adjacent islands.

Pelagic zone

Open sea, away from the shore.

Periphyton

Attached microscopic organisms growing on the bottom or on other submerged substrates.

Permeable groin

Groin with openings large enough to permit passage of appreciable quantities of littoral drift; see *groin*.

Phytoplankton

Planktonic plant life.

Pier

A structure, usually of open construction, extending into the water from the shore. It serves as a landing and mooring place for vessels or for recreational uses. Includes trestles, platforms, and docks.

Pile

Long, heavy timber or section of concrete or metal driven or jetted into earth or seabed for support or protection.

Pile cluster

Dolphin; group of adjacent piles.

Pile dike

Dike construction of piles.

Pile, sheet

Pile with generally slender flat cross section, meshed or interlocked with like members to form wall or bulkhead.

Piling

Group of piles.

Pioneer species

One capable of establishing itself in a barren area.

Plankton

Suspended microorganisms with relatively little power of locomotion that drift in water and are and are subject to action of waves or currents.

Point

Outer edge of any land area protruding into water, less prominent than cape.

Point buoy
Mooring buoy, usually for single vessel; see *buoys* and *floats*.

Port
Place where vessels may discharge or receive cargo.

Productivity
Rate of production of offspring, or fixation of solar energy.

Quay
Stretch of paved bank or solid artificial landing place parallel to navigable waterway used as loading area.

Ramp
A uniformly sloping platform, walkway, or driveway. The ramp commonly seen in the coastal environment is the launching ramp which is a sloping platform for launching small craft.

Reef
An offshore chain or ridge of rock or ridge of sand at or near the surface of the water. An artificial reef is a similar chain or ridge built up by man to resemble a natural reef.

Retaining wall
Wall built to keep bank of earth from sliding or water from flooding; see *bulkhead*.

Revetment
A sloped facing built to protect existing land or newly created embankments against erosion by wave action, currents, or weather. Revetments are usually placed parallel to the natural shoreline.

Ria
Long, narrow inlet with depth gradually diminishing inward.

Riprap
Layer, facing, or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of structure or embankment; see *revetment*.

River datum
Reference plane for river; each river has a characteristic datum.

Roadstead (also road)
A place less enclosed than a harbor where ships may ride at anchor.

Rubble
Rough, irregular fragments of broken rock.

Rubble-mound structure
Mound of random-shaped and random-placed stones protected with cover layer of stones or specially shaped concrete armor units.

Sand

Rock fragments less than 0.75in (1.9cm) diameter.

Scouring effect

Removal of underwater material by waves and currents, especially at base or toe of a structure.

Seawall

Structure separating land and water areas, primarily designed to protect land from wave action; see

Sedimentation

Process of deposition of material, usually soil or organic detritus, in the bottom of a liquid.

Sessile

Attached to substrate and not free to move about.

Shingle

Any beach material coarser than ordinary gravel, especially with flat or roundish pebbles.

Shoreline, eroding

Shoreline which, by wave action, longshore current, or frequent storm activity is losing material.

Sill, sandbag

A small breakwater used for shore protection which is constructed from sand filled nylon tubes. Sandbag sills are usually placed parallel to the shoreline and just below the intertidal zone.

Silt

Loose sedimentary materials with rock particles less than 0.05 mm diameter.

Slip

Berthing space between two piers.

Spandrel (bridge)

A bridge with a series of arches supporting the roadway.

Spawning

Production and deposition of eggs, with reference to aquatic animals.

Spit

Small point of land or narrow shoal projecting into body of water from shore.

Spring tide

Occurs at or near time of new or full moon and rises highest and falls lowest from mean sea level.

Stone, derrick

Stone heavy enough to require mechanical means of handling individual pieces, generally 1 ton (0.91 metric ton) and over.

Storm tide

Rise above normal water level on open coast due to action of wind stress on water surface.

Structure support

Pilings or other structures with principal function being the support of a structure which extends over the water.

Substrate

Solid material upon which an organism lives or to which it is attached.

Succession

Sequence of communities which replace one another in a given area.

Taxon (pl taxa)

Any taxonomic unit or category of organism; e.g., species, genus, family, order, etc.

Terrestrial

Growing or living on or peculiar to the land, as opposed to the aquatic environment.

Terrigenous

Relating to oceanic sediment derived directly from destruction of rocks on earth's surface.

Tetrapod

A type of precast concrete armor unit with four legs used for facing rubble-mound structures.

Tidal datum

Plane or level to which elevations or tide heights are referenced. These vary for different coastal regions.

Tidal flat

The sea bottom, usually wide, flat, muddy, and unvegetated which is exposed at low tide; marshy or muddy area that is covered and uncovered by the rise and fall of the tide.

Tide gate

An opening through which water may flow freely when the tide or water level is low or high but which will be closed to prevent water from flowing in the other direction when the water level changes.

Toe, bulkhead

The base of a bulkhead, the lowest part.

Tolerance

Relative capacity of an organism to endure or adapt to an unfavorable environmental factor.

Tombolo

Bar or spit connecting an island or structure to the mainland or to another island.

Toxicant

Substance that kills, injuries, or impairs an organism.

Toxicity

Quality, state, or degree of the harmful effect resulting from alteration of an environmental factor.

Training works

Structure to direct current flow; see *jetty*.

Trestle

Braced framework of timbers, piles, or steelwork; see *pier*.

Turbidity

Deficient in clarity; muddiness, murkiness.

Vertebrate

Animal having an internal skeletel system.

Walers

Horizontal members attached to piles in bulkhead; see Figure 27.

Wave runup

The rush of water up a structure or beach on the breaking of a wave.

Weep holes

Drainage hole in a structure allowing release of groundwater to prevent a buildup of water behind the structure.

Weir jetty

An updrift jetty with a low section or weir over which littoral drift moves into a pre-dredged deposition basin which is periodically dredged.

Wharf

Structure built on shore so vessels may tie alongside.

Zooplankton

Planktonic animal life.

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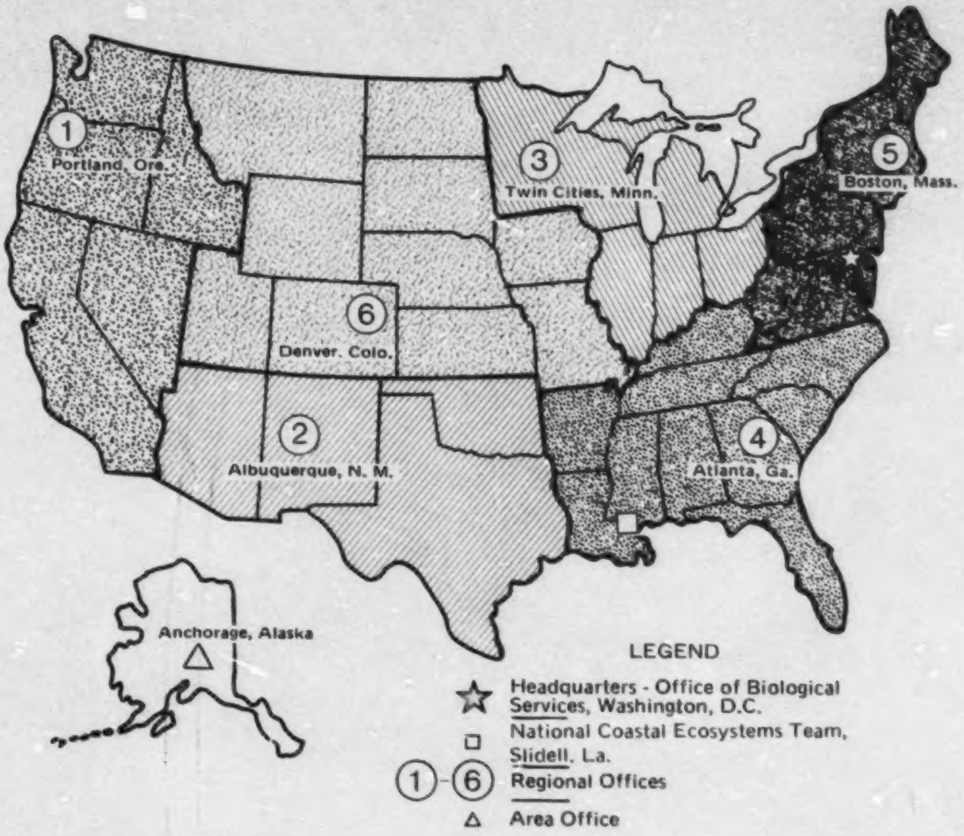
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